NCHRP

SYNTHESIS 372

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Emerging Technologies for Construction Delivery

A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Emerging Technologies for Construction Delivery

A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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Cover photograph: Dual GPS blade antennae on dozer
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FOREWORD

By Staff
Transportation
Research Board

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice.*

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

This synthesis presents information on the use of five emerging technologies for transportation construction projects: global positioning systems for layout, machine guidance, and quantity tracking; handheld computers for construction records; automated temperature tracking for concrete maturity monitoring; four-dimensional computer-aided drafting modeling for constructability analysis and improved communications; and web-based video cameras for remote project monitoring. The synthesis reports on the current state of each of the five technologies and their potential benefits for transportation agencies in the delivery of construction projects. The following characteristics are provided for each of the technologies: description, benefits, extent of use, barriers to use, instances of successful implementation and procedures, unresolved issues, and unintended consequences. It also discusses the current level of use and documents lessons learned from agencies with experience in implementing the targeted technologies. Other technologies discussed include virtual reality, building information models, and radio frequency identification. The information will form a foundation from which state and provincial highway agencies can begin the process of performing benefit–cost analysis as a first step to adopting those technologies that seem the most promising.

A survey questionnaire was distributed to U.S. departments of transportation through a web-based survey application, and was also sent to select Canadian transportation agencies. Responses were received from agencies across the North American continent. In addition, a literature search was conducted of academic, governmental, industrial, and commercial resources to provide a solid theoretical and anecdotal basis for the review of each technology.

John Hannon, University of Southern Mississippi, Hattiesburg, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

EMERGING TECHNOLOGIES FOR CONSTRUCTION DELIVERY

SUMMARY

This synthesis study provides information on the use of five emerging technologies by transportation agencies for construction projects. The technologies explored are:

1. Global positioning systems (GPS) for layout, machine guidance, and quantity tracking;
2. Handheld computers for construction records (e.g., inspection, materials testing, and quantity tracking);
3. Automated temperature tracking for concrete maturity monitoring to optimize concrete placement for bridge and road construction;
4. Four-dimensional (4D) computer-aided drafting (CAD) modeling for constructability analysis and for improved communications (public outreach and visualization of project staging); and
5. Remote project monitoring with web-based video cameras.

The TRB Committee on Application of Emerging Technologies (AFH30) described the need for exploiting current advancements in construction technology in the following terms:

> As the new century approaches and the baby boomers age and begin to retire, labor shortages are anticipated. Therefore, new construction automation, equipment, and techniques will be needed so the equivalent work can be performed with fewer workers. The automation is likely to prove more reliable, efficient, and cost-effective as well.

Thus, using that belief as the backdrop, this study furnishes the necessary information for transportation officials to begin exploiting the five promising technologies, detailed herein. These technologies have reached a developmental maturity level to make them practical—if not imperative—tools in the delivery of construction projects. After conducting an extensive literature search, distributing and reviewing the transportation agency survey (41 state departments of transportation and 7 Canadian transportation agencies responded), and collecting additional information gathered from various subject-matter experts, it is clear that these technologies have proven their value in the field despite the industry's low adoption rate. The application of these technologies promises potential time and cost savings over time. A return on investment analysis is required to accurately justify incorporation of the technologies into the construction project life-cycle work-flow process of transportation agencies. Risks may lie in the fast development of new technologies and the relative lack of standardization and specification, rendering fiscal investments in technology systems that are quickly obsolete or that are unable to scale as required by the size of transportation agencies.

Several of these technologies are disruptive in nature. By disruptive innovation, we refer to technologies that, by their very essence, require changes in how business is conducted. Although the private sector, which is typically less bureaucratic and driven by the profit motive, can justify such process changes more quickly, public agencies must take a different route to incorporate change. The public agency attitude toward risk-taking as well as the autonomous segmentation of transportation agencies (many regional offices with differing levels of technology application and work-flow processes) may require a concerted effort toward standardization and cost justification to realize the potential benefits of these technologies.

The five technologies addressed in this report are components that constitute what some are terming "smart jobsites." They can be used together, in conjunction with other supporting technologies, to create a more efficient system of construction project delivery. The motive for adopting these tools is not necessarily payroll reduction overheads, but the empowerment to compress construction schedules, spend payroll time in critical thinking activities (management) instead of administrative functions, and provide access to information more quickly so as to justify the investment. Faster project delivery, without decreases in quality, is a benefit to the traveling public. In addition, early adopters of these technologies report an increase in quality, a decrease in rework and change orders, and improved safety for both project and nonproject personnel.

The smart jobsite concept is realizable today. The five technologies explored in this synthesis, along with background support tools such as broadband network connections and databases, have proven to be workable and beneficial for some contract stakeholders. With regard to transportation agencies, the synthesis survey revealed common responses across the technology types as to the restriction of their adoption or use. The most prevalent responses regarding barriers to implementation of the technologies are:

- Budget restraints,
- Absence of specifications,
- Ignorance of the technology's potential benefits,
- Lack of end-user technical skills (personnel skills), and
- Agency procedural issues.

For transportation agency budgeting to include the cost of these technologies, the benefits of their use must be known for return on investment decisions. If the agency can procure the technology, it must have available personnel skilled in its use for implementation. Finally, like all organizations that adopt technology that effects work flow processes, it should be prepared to change procedures (specification) of organizational operation as needed.

Summaries of the synthesis findings specific to each technology studied follow.

A **Global Positioning System** (GPS) is a technology that allows instantaneous determination of position. The GPS tools use timing of radio signals from satellites to determine x, y, and z location coordinates. This ability is very useful for surveying in the design engineering phase of project life cycles as it decreases the time required to acquire terrain information and the manpower required to collect it. In the construction delivery phase of projects, GPS is used to quickly spot-check grade elevations and structure locations, and identify quantity differences between existing and design plan coordinates. With appropriate hardware and software, construction sites can be graded with significantly less staking and manpower. Earthmoving equipment can use GPS systems for determining blade and bucket angles for precise excavation and embankment of earthwork, resulting in faster and more accurate grading, less rework, less time waiting for surveys, and less machine idle time.

Utilization of GPS technology for design, layout, machine guidance, and quantity tracking provides the following additional benefits in time savings.

- Engineering design,
- Labor resources,
- Equipment resources, and
- Construction work processes.

However, the study revealed the following barriers to GPS adoption:

- Lack of transportation agency specification of its use,
- Scarcity of available GPS equipment,

- A lack of understanding regarding the technology's potential and proven benefits,
- Agency budget restraints,
- Scarcity of personnel trained to use GPS tools,
- Agency organizational procedural issues, and
- Issues with the design function of the project delivery life cycle.

One-quarter of the respondents reported no experience with GPS technology and another quarter have experience with fewer than a dozen projects. The remaining agencies are split with varying levels of experience with GPS in delivery of their projects. Of the agencies reporting GPS experience, layout and staking applications are clearly the favorite and most utilized, followed by machine guidance, pay quantity measurement, and structure locating.

Of agency opinions regarding factors that inhibit the use of GPS technology in the delivery of construction projects, the most frequent answer was the lack of agency specifications regarding GPS use. The next most popular responses were the scarcity of GPS equipment, followed by an agency's ignorance of the benefits of using GPS in the construction delivery process and then by a lack of user technical skills. Other frequent responses included budgeting, agency procedural issues, and agency and consultant design function.

Agency personnel reported that the most significant contribution of GPS to a successful implementation is the influence of designer and surveyor functional roles.

Among the most significant unresolved issues regarding GPS adoption by transportation agencies (and the industry in general) is that of CAD design practices. Original designs in three dimensions (3D) issued for use by contractors would certainly spur the adoption of GPS by contractors. Most designs currently issued by transportation agencies and consultants are two-dimensional, requiring that those who wish to leverage GPS's benefits produce the 3D terrain models as an incidental cost of construction.

Some unintended consequences regarding agency implementation of GPS systems include (1) legal issues concerning contract documents, (2) fair access to the public sector contracting market, and (3) professional credentials of technicians locating survey points for government contract payment.

Handheld computers (HHC) are self-contained electronic devices that fit in the palm of a user's hand and possess, at a minimum, enough computer processing power to surpass the functions of an electronic personal organizer and to run software applications that can extend their built-in functionality.

The survey questionnaire revealed that of 50 transportation agency responses, 24 agencies (43%) have not implemented HHC technology on any projects. Only four agencies (7%) responded as utilizing the technology on all of their projects. Approximately 14 agencies of all reporting agencies (25%) have implemented the technology on most projects. Of the agencies reporting use of handheld technology in construction project delivery, the most widely used application is the inspector's documentation of daily construction activity. The second most utilized application is using HHC to document or track contract working days charged against the contractor, "contract time tracking." The third most significant application of HHC is to track project materials.

When queried as to which project participants are utilizing HHC technology in specific applications, the responses revealed that transportation agencies have embraced the technology in greater quantities than have either the project consultants or the contractors (with the exception of GPS and voice communication).

The survey queried transportation agency respondents as to their opinions regarding factors that hindered HHC technology implementation at their agency. The most popular response was the cost of implementation, followed by software interoperability issues and end-user training. The third most popular responses were that: (1) the screens are not viewable in direct sunlight, (2) procedural issues within the agency, and (3) general unawareness of the benefits that the technology can provide.

When agency personnel were queried as to the factors that most contribute to successful HHC use in their agencies, the most popular response was that end-user training is a high to medium factor in successful implementations. Ease of use was reported as the next most significant factor followed by vendor/supplier support and agency technical support. Also scoring significantly high was knowledge of expected benefits.

Automated concrete temperature and maturity tracking is a technique that uses technology for monitoring portland cement concrete while it cures or hydrates in place. Based on the ASTM C1074 maturity method for estimating concrete strength, it can either substitute for or enhance the existing processes of testing field and lab test cylinders. The primary benefits of implementing this technology are:

- Provides relatively simple, efficient, and effective approach for making reliable determinations of in-place concrete strength during construction.
- Allows earlier determination of when formwork can be removed, post-tensioning applied, or a concrete placement can be exposed to live loads, thereby resulting in accelerated construction cost savings.
- Improves quality control when used in conjunction with, or instead of, testing separately cast specimens to measure concrete strength because the strength estimates from the maturity method are based on data from the actual structure (instead of separate lab specimens).
- Give instantaneous notification of extreme temperatures or thermal gradients within a concrete structure that may affect quality, thereby allowing remedy or documentation.

Thirty-nine of 47 responding agencies (83%) have used the maturity method on ten or fewer projects. More than half of the respondents (25) have not used the technology at all. Of the agencies reporting use of the maturity method, by far the most popular construction application is paving, followed by bridge construction.

The survey queried transportation agency respondents as to their opinions regarding factors that they believe have hindered automated concrete temperature tracking and maturity monitoring technology implementation at their agency. The most popular responses were contract specification issues and a general unawareness of the benefits provided by the technology. An equal number of agencies reported cost and agency procedures to be a hindrance to adoption of the technology.

When queried as to the factors that most contribute to successful automatic monitoring of concrete temperature and strength by use of the maturity method, agency personnel reported the two most highly rated and chosen factors as ease of use and knowledge regarding the benefits of using the technology.

4D CAD models consist of 3D digital project plans with the additional integration of a construction work progress schedule (time). This product then simulated visualization of the design model's intentions according to the scheduling application's timing and logic. The viewer can see the facility's construction components evolve in time-lapse into the completed product.

Benefits gained by implementation of the technology include:

- Design change feedback
- Material fabrication and procurement

- Constructability review
- Communication of building methods or systems
- Quantity tracking
- As-built documentation
- Public relations
- Schedule optimization
- Incidental project resource requirements
- Improved change management.

4D CAD modeling currently is not significantly used by transportation agencies according to the synthesis survey responses. Of 47 transportation agencies responding to this section of the questionnaire, only 5 indicated experience with 4D CAD modeling. Of the small sample of respondents who have experience with 4D CAD, their primary use of the driving application appears to be communicating construction project plans to the public. Construction delivery-related applications have some use, whereas quantity tracking has none.

Agencies using 4D CAD reported factors that restrict implementation. The sample group is so small that single responses designate the rankings of the factors. Topping the list of restrictions is agency procedural issues, followed by a tie between a lack of end-user technical skill and training and unawareness of the potential benefits. All of the categories received votes, including software interoperability issues, contract specification issues, conflicting technology standards, agency budgeting, hardware availability, noncooperation of designers, and "other."

The literature review revealed the following unresolved technical and commercial issues that pertain to the utilization and implementation of 4D CAD modeling:

- Equitable methods to distribute modeling costs to project participants and beneficiaries.
- Multiple project stakeholder buy-in.
- New models must be created for each project in the transportation industry as the terrain or site model is typically a large percentage of the 3D model.
- New models must be created for differing levels of required model detail.
- Access to sophisticated modeling tools requires licensing.
- Cost associated with providing collaborative environments.
- Analysis methods are not yet fully integrated into the simulation.
- Accommodation of differing design, work process, and other database schemas by the project stakeholder involved.

Unintended consequences of implementation of this technology may include:

- Forced early collaboration and time expenditure by parties to the contract.
- Fear of mistake exposures on the part of designers.

Web-based video project monitoring refers to capturing construction project images in real-time, time-lapse, or streaming video formats.

Survey responses revealed that the extent of respondent agency use of web-based video camera monitoring of construction projects is as follows: Of 47 respondents, 64% do not use the technology, whereas 36% have used it on 10 or fewer projects. Of the respondents who have used this technology, more than 72% provide the service as a benefit to the public as a display on agency websites. Nine agencies reported the collection of images for legal and inspection purposes, five reported the collection of images for time-lapse replay, and two use the technology for traffic monitoring.

Agency personnel reported budget issues and benefit unawareness as the leading factors that restrict the use of the technology in their agencies

Agencies that have successfully employed the web-based camera technology report that, in their opinion, support from hardware and software vendors and suppliers is the most important factor contributing to that success.

Other technologies that are currently finding applications in the construction industry include:

- Virtual reality
- Building information models
- Radio frequency identification
- Ground penetrating radar
- Electromagnetic sensors
- Laser detection and ranging
- Virtual as-built photography.

Anticipated future developments include:

- Nondestructive testing and monitoring in response to environmental and safety concerns.
- Technologies for monitoring, guiding, and coordinating construction equipment and robots:
  - Inertial navigation systems,
  - Active beacon systems,
  - GPS,
  - Ground-based radio frequency systems,
  - Ultrasonic and optical systems, and
  - Radio frequency identification systems.
- Smart structures.
- Four-dimensional visualization.
- Total electronic integration.

Future research needs may include the following:

- Documented case studies with emphasis on return-on-investment analysis and implementation costs.
- Case studies and research concerning the balancing of contractual risks and rewards on projects using digital modeling that are specific to the transportation industry.

CHAPTER ONE

INTRODUCTION

BACKGROUND

In the past few years, information technology (IT) advancements with construction applications have emerged from research, development, and conceptualization to commercial markets where they are now available for implementation. Hardware and software applications are available today that can be practically used for the increased efficiency of construction work processes. Although some of these tools are in their technological infancy and have been utilized only by early adopters, others have been around long enough to see widespread adoption outside the construction industry. In 2000, TRB asked each of its standing committees to report on transportation in the new millennium. Committee AFH30, the Committee on Application of Emerging Technologies, listed its unique perspective on promising technologies to satisfy the coming century's needs to deliver construction projects using automation as the cornerstone. It stated that "construction crews will have to perform their work more rapidly" owing to the increased demand on the existing transportation network and the cost of disrupting traffic for construction and maintenance operations (Haas et al. 2000). Committee A2F09 cited a number of promising technologies that would appear to satisfy those constraints. Seven years later, this synthesis reports on the progress made toward achieving the vision articulated by that TRB committee.

The objective of this report is to consolidate and synthesize information on five technologies that have evolved to stages of practical availability and affordability. This will form a foundation from which state highway agencies (SHAs) can begin the process of performing benefit-cost analysis as the first step to adopting those technologies that seem promising. To do so, SHAs must have an understanding of how the technology can benefit the targeted work-flow process. In addition, they must have an understanding of what the technology is and how it works, along with quantification of direct and indirect costs of required hardware, software, user training, and implementation. This synthesis reports on the current state of the five technologies and their potential benefits for transportation agencies in the delivery of construction projects. It also reports on the current level of utilization of these technologies by transportation agencies in the United States and Canada, as well as documents "lessons learned" from agencies that have experience with implementing the targeted technologies.

The scope of information reported in this synthesis is limited to the following five technologies:

1. Global positioning systems (GPS) for layout, machine guidance, and quantity tracking.
2. Handheld computers (HHC) for construction records (i.e., inspection, materials testing, and quantity tracking).
3. Automated temperature tracking for concrete maturity monitoring to optimize concrete placement for bridge and road construction.
4. Four-dimensional computer-aided design (4D CAD) modeling for constructability analysis and improved communications (i.e., public outreach and visualization of project staging).
5. Remote project monitoring with web-based video cameras.

The report is organized by technology type. The results of the literature review and the agency survey will be reported individually in each chapter. Each technology's chapter contains the following sections:

- Description of the technology;
- Benefits of the technology;
- Extent of the technology usage by transportation agencies, consultants, and construction contractors;
- Barriers to the technology's implementation;
- Report of successful implementation factors and procedures;
- Unresolved issues pertaining to the technology's use and implementation; and
- Unintended consequences of the technology use and implementation.

In addition to gaining a basic understanding for the technologies and how they work, readers of this report should benefit from the following:

- A general understanding of the resources required to implement the technology along with consideration of the direct costs involved in application of the technologies.
- The current extent of use and adoption of the technologies by a representative sample of transportation agencies.
- Factors, issues, and procedures that have benefited transportation agencies that have either successfully adopted or are attempting to adopt the technologies.

- Factors, issues, and procedures that have hindered the adoption of these technologies in transportation agencies.
- New technologies that are evolving or being used by transportation agencies in the delivery of construction projects.
- Further research that should be conducted to facilitate the efficient delivery of construction projects by transportation agencies in relation to IT.

Finally, this report provides a snapshot of each technology that provides the requisite salient information that will allow SHA officials to initiate business decisions to explore and experiment with the five targeted technologies. This synthesis report will allow them to do so without having to "reinvent the wheel" or make the same mistakes as their predecessors who furnished information to this report. This is probably the most valuable aspect of this particular study.

SCOPE OF RESEARCH

The consultant conducted a literature search of academic, governmental, industrial, and commercial research papers and reports related to the five technologies, resulting in the creation of a list of more than 200 relevant documents. The literature review focus was to provide a solid theoretical and anecdotal foundation for the review of each technology. Based on the preliminary results of the literature search, a survey questionnaire was developed that was subsequently reviewed, piloted, and approved by the Synthesis Topic Panel. The survey questions are included in Appendix A. The questionnaire was delivered to 51 U.S.DOT agencies (including Puerto Rico) by means of e-mail through a web-based survey application; 43 responses from 41 states were received. The survey was also distributed to select Canadian transportation agencies and seven responses were received. A list of agencies responding to the survey questionnaire can be found in Appendix B. Figures 1 and 2 (and Appendix C) show the geographic distribution of respondents and synopsizes their current use of the five technologies of interest. One can see that the information used in this study covers the entire North American continent and, as a result, articulates the state of the art based on a broad cross section of experiences across the spectrum of state-level environmental and technical conditions. Also interesting to note is that none of the responding agencies use all five of the subject technologies.

Survey analysis has been directed toward identifying practices that are likely to result in contributions of both successful and unsuccessful projects. After identification of such practices, a structured case study format for each technology was developed for further investigation of the features of the best practices. The case study process provides an illustrative framework to extract lessons learned from highly successful practices. Considerable constructability improvements may be possible through emulating practices that have been identified as critical to project success. The following chapters furnish the analysis of the output from both the literature and the survey respondents.

FIGURE 1 United States survey respondents (shaded states) and reported technology use. G = GPS; H = HHC; P = PCC; 4 = 4D CAD; C = webcam.

FIGURE 2 Canadian survey respondents (shaded provinces/areas) and reported technology use. G = GPS; H = HHC; P = PCC; 4 = 4D CAD; C = webcam.

CHAPTER TWO

GLOBAL POSITIONING SYSTEMS

DESCRIPTION OF TECHNOLOGY

Several excellent definitions of GPS exist in the body of literature collected including the following:

> GPS is a space-based, radio-navigation system that provides worldwide, all-weather, three-dimensional position, velocity, navigation, and time data to both civilian and military users. Potential uses for GPS within the highway community are diverse and range from providing traveler information to mapping (GPS technology can be integrated easily with Geographic Information Systems). GPS can provide a very accurate digital map of the highway infrastructure. The technology operates on the principle of triangulation—if the difference from an observer to three known points can be measured, the position of the observer can be calculated. The system includes at least 24 satellites in orbit 19,320 kilometers (12,000 miles) above the earth and inclined at 55°. These satellites continuously broadcast their position, a timing signal, and other information. By combining the measurements from four different satellites, users with receivers can determine their 3-dimensional position, currently within 4–20 meters (13–66 feet) (Global Positioning System Surveying n.d.).

GPS satellites communicate with ground control stations (base stations) through radio waves, which in turn communicate by means of radio to the end users. The technology uses the concept of triangulation from satellite signals to determine a three-dimensional (3D) (*x, y, z* coordinate) position on the ground. Triangulation consists of computing the distance from the ground station to at least four different satellites at any given time. The distances to the receiver are determined by measuring the travel time of radio signals from each of the satellites. Atmospheric moisture and distortions of the radio waves in the ionosphere, as well as the satellite's location in the sky, influence the accuracy of the measurements, which causes an intrinsic maximum error of 45 ft in the raw data. To compensate for the error, differential GPS (DGPS) systems use a correction mechanism by use of a fixed receiver that has known coordinates. Several DGPS systems are currently available:

- Ground stations: These systems combine the ranging signals from the satellites with correction signals from the fixed-base station. The location of the DGPS base station is established by collection of GPS signals over a period of time. Thousands of signal readings by the base station are averaged to correct the normal propagation errors to within 1 mm of accuracy.
- Coast Guard Maritime DGPS: This is a fixed-ground receiver (beacon) system that enables real-time differential correction accuracy within 1 to 3 m. The beacons are present around the coastlines of the United States, Puerto Rico, Alaska, and Hawaii.
- Wide Area Augmentation System: This is a combination of satellites and ground stations that enable real-time differential correction within 3 m, 95% of the time.
- OmniSTAR: This worldwide system of satellites and network control stations facilitates real-time differential correction of raw data. OmniSTAR provides two accuracy levels of service, both of which must be licensed for access.
- Real-time kinematic GPS: Real-time kinematic systems require two or more receivers to be operated simultaneously. Radio waves from a base station receiver transmit corrections to a roving receiver (also receiving signals from the satellites). A computer at the rover receiver processes the readings in real time to produce an immediate determination of its location (Lin 2004).

Determination of a computed position is the purpose of GPS. Functionally it is used for guiding individuals from one location to another (navigation), monitoring the location and movement of people or assets (tracking), creating maps (mapping and surveying), and bringing precise timing (timing) (Caldas et al. 2004; *GPS Integration* . . . 2005). Depending on the application for which GPS is utilized, different combinations of equipment and accuracy are required. Table 1 displays typical grades of accuracy ranges for three intended uses: recreational, mapping, and survey.

GPS usage on transportation projects can manifest itself during both the design and construction stages of delivery. The engineering design phase can apply GPS for surveying of existing topography of the construction project by agencies and consultants. Agency personnel or consultants typically provide survey control and track the quantity of material moved by the contractor (by unit of measure specified) for contractor payment purposes. In the project's planning and programming phases, agency or consultant designers can integrate GPS with geographical information systems (GIS) to provide increased position data accuracy and more efficient (cheaper) data collection (Czerniak 2002). The two primary uses of these technologies early in the project life cycle are for surveying and mapping.

A requirement for one of the most important applications of GPS technology in the proceeding construction phase, machine guidance, requires creating, sharing, and using 3D

TABLE 1
GRADES OF ACCURACY IN GPS UTILIZATION

Grade	Accuracy (ft)		Use	Base Station Requirement
	Horizontal	Vertical		
Recreational	15–30	100	Sport/rough location	No
Mapping	3–10	10–30	GIS-type mapping	Yes
Survey	0.03–0.10	0.10–0.15	Land survey/photogrammetry	Yes

terrain models. To leverage the advantages of the technology throughout project delivery, the design phase must produce this model. The availability of a 3D terrain model containing both the existing and design ground contour elevations from existing CAD software design features is preferred. However, most agencies are currently producing traditional 2-dimensional (2D) drawings or, for various reasons, not sharing their 3D designs with contractors. This forces contractors who are implementing GPS technology for machine guidance to produce their own models. A common practice is for contractors to produce a Triangular Irregular Network (TIN) terrain model from a 2D design. The TIN consists of elevation points connected to form triangular planes, which represent the planes on a terrain surface. Figure 3 displays an image of a 3D design model, whereas Figure 4 displays a computer screen image of a TIN model.

In the construction phase, the technology can provide efficient methods for tracking materials and determining earthwork quantities by any of the contract stakeholders. Contractors can use the technology for machine guidance during excavation and embankment activities.

As stated earlier, one GPS application is the support of earthmoving operations in the delivery of construction projects. These functions include communication between the satellites, base station receivers, the earthmoving equipment (blades and buckets), and the equipment operators, as well as quantification of the differences between existing and design ground elevations. Transportation projects typically lend themselves to varying proportions of earthmoving by the contract awardees.

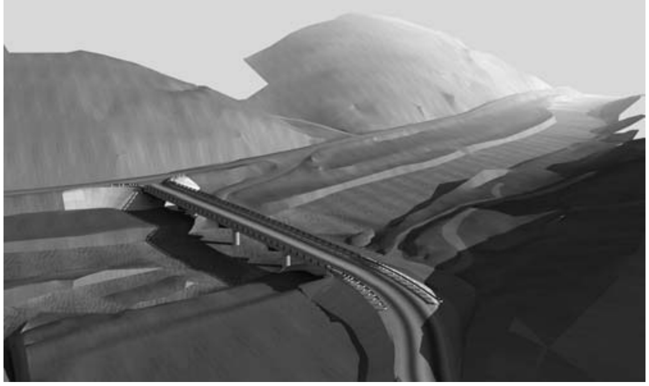


FIGURE 3 Computer display of 3D terrain model (*Courtesy*: Bentley Systems, Inc.).

The hardware components required to use GPS in survey grade applications follow:

- A GPS receiver and antenna for satellite signal reception.
- A radio and antenna for GPS signal communication between GPS receivers.
- A computer for GPS coordinate translation on a rover based on the known fixed-base station coordinates. In tandem with software, the computer functions as an instructional display device for a human end user. Some systems provide an interface to a construction machine's hydraulic system controls, thereby automating machine direction with reduced need for machine operator control.

Different combinations of these equipment components are assembled into systems dependent on project conditions and the GPS functionality desired. Large surveying projects in the design stage require that high-grade receivers and radios be networked to span the large geographical distances that can encapsulate the boundaries of large projects such as highways. A growing network of GPS base stations exist that have been placed by various public agencies and private organizations for the purpose of facilitating mapping and survey-grade GPS capabilities. These networks include Continuously Operating Reference Stations (CORS), a network sanctioned by the National Geodetic Survey. The Survey also established the National Spatial Reference System, which is a nationwide coordinate system that specifies latitude, longitude, and elevation through a network of marked control

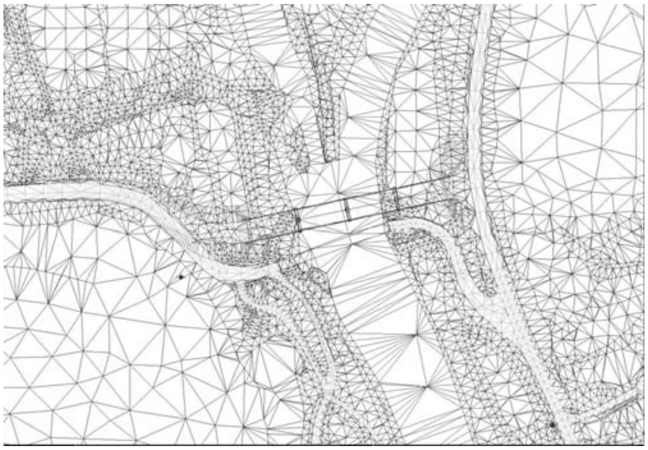


FIGURE 4 Computer display of TIN model (*Courtesy*: Bentley Systems, Inc.).

points. Several transportation agencies are actively involved in building CORS networks within their state boundaries.

For GPS layout applications on construction jobsites, a base station is mounted in a fixed location within 10 km (6 miles) of the jobsite. Rover receivers for networking to the base station are available in the following multiple forms:

- Tripod-mounted hardware that combines the components of GPS receiver, radio receiver, and accommodating antennas, and receives location data from satellites and correction data from the base station.
- Mobile pole-mounted receivers are carried by field personnel and act as a second rover. They can identify location and elevation points on the site's ground surface through communication with the base station and GPS software. Separate computers or controllers can be attached to interpret the data from the receivers.
- The GPS software applications can reside on HHCs, which then perform operations such as volume computations, staking locations for layout, and grade elevation checks.
- Rovers can be mounted in the back of pickup trucks and even in backpacks for material tracking applications. These field rovers require batteries for power supply. Currently, lithium ion batteries allow power supply for approximately 10 h before requiring recharge.

Figures 5 through 8 display GPS equipment for use in GPS layout of construction jobsites.

For GPS machine guidance, the same hardware components are required in a slightly differing configuration. A fixed-base station is required, and single or dual receivers (sensors) are mounted on the earthmoving equipment. The configurations are used successfully with excavators, dozers, scrapers, and motor graders. Using design surface elevations from 3D models contained on a computer, the machine-mounted GPS receivers guide the equipment blade or bucket to the appropriate levels and angles to produce the desired grade or elevation. This is accomplished either by operator visualization of the onboard computer, whereby the operator engages the appropriate machine controls, or automatically through interface controls with the machine's hydraulic system, which engages the blade or bucket position. Figures 9

FIGURE 5 GPS antennae, receiver, and HHC tripod (*Courtesy*: McAninch Corporation).

FIGURE 6 GPS antennae and computer (*Courtesy*: McAninch Corporation).

FIGURE 7 GPS field computer (*Courtesy*: McAninch Corporation).

FIGURE 8 GPS field computer and stylus input (*Courtesy*: McAninch Corporation).

through 22 display GPS hardware and software used for machine guidance.

For GPS quantity tracking, the base station receiver and any rover receiver can instantly calculate excavation areas, trench volumes, stockpile volumes, and other measurements without the need to enlist a small crew of surveyors to record topographical elevations. A pole-mounted receiver, an accompanying HHC, and a trained operator are all that are required to obtain accurate length, area, and volume quantities.

The caveat in all GPS scenarios is that they require a clear line of site from the satellites to the receivers. Terrain limitations, tall buildings, and tree cover are detriments to GPS satellite communication. A new generation of satellites (L2) that will send signals in a different frequency to receivers may alleviate some of these hindrances in the future.

FIGURE 9 Cab-mounted GPS receiver (*Courtesy*: McAninch Corporation).

FIGURE 10 GPS receiver and blade antennae (*Courtesy*: McAninch Corporation).

Software requirements include the availability of a 3D terrain model containing both the existing and design ground

FIGURE 11 Dual GPS blade antennae on dozer (*Courtesy*: McAninch Corporation).

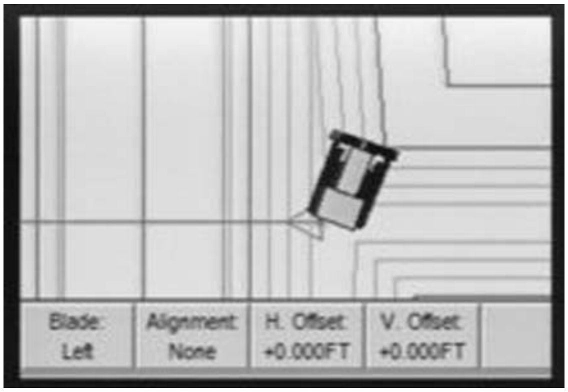
FIGURE 12 Dual GPS antennae on scraper pan (*Courtesy*: McAninch Corporation).

FIGURE 13 Dual GPS antennae on excavator counterweight (*Courtesy*: McAninch Corporation).

FIGURE 14 GPS antennae close-up (*Courtesy*: McAninch Corporation).

FIGURE 15 Dual GPS blade antennae on dozer (*Courtesy*: McAninch Corporation).

FIGURE 16 Fine grading with GPS-enabled dozer (*Courtesy*: McAninch Corporation).



Blade:	Alignment	H. Offset:	V. Offset:
Left	None	+0.000FT	+0.000FT

FIGURE 17 Machine operator plan contour view (*Courtesy*: McAninch Corporation).

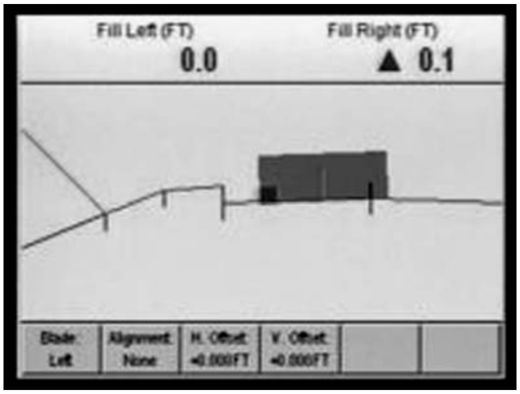

Fill Left (FT) 0.0
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FIGURE 18 Machine operator profile view (*Courtesy*: McAninch Corporation).

FIGURE 19 Machine-mounted GPS computer (*Courtesy*: McAninch Corporation).

contour elevations. Software is also required to control the basic GPS hardware functions of radio signal reception, interpretation, and differentiation. Additional software interprets GPS positioning in relation to the design terrain models and is used for machine operator control and field management for grade checking, spot locations, and quantity differentials. Most GPS software applications provide plan, cross-section, and profile views, as well as text and text data for the user. Figures 17 through 21 display screen shots of plan and profile views observed by construction machine operators and hardware configuration mounts for machine operator viewing.


Station 9763+57.53 m
CL Offset 24.00 m
Tilt 1:44.1
Cut Left 1.66 m
Cut Right 1.65 m

FIGURE 20 Cab-mounted GPS computer with light bars (*Courtesy*: McAninch Corporation).

FIGURE 21 Machine-mounted GPS computer (*Courtesy*: McAninch Corporation).

FIGURE 22 GPS rugged handheld computer (*Courtesy*: McAninch Corporation).

Figure 22 displays a ruggedized HHC for display of GPS information in the field.

BENEFITS OF TECHNOLOGY

The following are the benefits to be gained by using GPS compared with conventional surveying technology (see Table 2):

- Design engineering and surveying
  - GPS technology enables faster surveying and mapping for design than conventional methods when line-of-sight conditions allow communications with satellites. Time compression in the design phase shortens the overall project delivery timeline.
  - Many 2D design anomalies are found and corrected during the creation of required 3D models.
  - Digital project design plans can provide superior accuracy over conventional 2D drawings.
  - 3D plans provide more complete review for constructability before construction starts, allowing for a reduction in errors and omissions.
  - Utilizing GPS technology for surveying and mapping layout is simply faster than conventional surveying methods.
  - GPS is easily incorporated with GIS mapping.
- Construction staking
  - Although some staking is still required, the GPS technology eliminates the need for iterative staking of different project design layers.
- Machine guidance
  - Because GPS allows for the most efficient operation of earthwork machinery, less operator time is required for construction, idle time, and rework.
  - GPS machine-guided earthmoving results in greater accuracy and reductions or elimination of finish grading requirements.
  - Use of GPS allows for the use of less-experienced machine operators.
  - Places design in front of operator (Alsobrooks and Townes 2005).
  - Unlimited machines can be operated from a single GPS base station (Alsobrooks and Townes 2005).
  - Line of site is not required for instrumentation (Alsobrooks and Townes 2005).
- As-built/quality assurance/quality control (QA/QC) documentation
  - One individual can locate and document exact *x*, *y*, and *z* positions (labor count of one required) with proper equipment.
  - GPS is easily incorporated with GIS mapping.
- Time savings
  - Labor resource savings: While required construction of 3D terrain models (TIN) requires more engineering labor up-front in the design process, once digital 3D models are constructed and reviewed for quality, labor savings occur in construction delivery as follows:
    - △ Equipment resource savings: Earthmoving equipment time is maximized by GPS accuracy when the machines are equipped with reception antennae, thereby increasing machine precision and accuracy, or simply by the use of field crews who can spot-check conventional equipment in real time. Machine idle time can be reduced when there is less waiting for excavation and embankment staking and clarifications. Finish grading iterations are lessened or nullified because of GPS accuracy, resulting in a reduction of machine hours. Equipment utilization of up to 30% can be realized (Alsobrooks and Townes 2005).
    - △ Construction work process: The earthwork construction tasks are shortened because:
      - ◦ Contractors can mobilize to the site and begin work without waiting for surveyors to position grade stakes for the initial lifts.
      - ◦ Contractors can check grades and recheck spot locations immediately versus calling and scheduling a survey crew.
      - ◦ Contractors can devote the time saved in layout and grade checking to machine movement and cycle-time efficiency.
      - ◦ Jobsite grade and location errors are more easily spotted and corrected with GPS technology than with reliance on 2D drawings and surveyor's grade stakes, thus reducing rework.
      - ◦ Construction field managers can make decisions more quickly and accurately because position and grade information is provided in real time.

TABLE 2
BROAD BENEFITS OF GPS TECHNOLOGY USE

Application	Process Improvement	Resource(s) Saved
Design surveying	Reduces field crews and facility design-phase duration; replaces aerial photogrammetry	Labor count, man-hours, consultants, project duration
Staking	Reduces field crews, iterations, and errors	Labor count, man-hours
Machine guidance	Reduces staking iterations, machine operator reliance on physical stakes, and physical staking	Labor count, man-hours, project duration, equipment-hours
As-built documentation	Reduces field crews and inspection time	Labor count, man-hours

- There are contractor and agency labor savings when measuring and documenting (in situ) as-built quantities and pay-quantity management.
- Erosion control can be implemented as construction sequences (Alsobrooks and Townes 2005).
- Construction can proceed during any 24-h shift in most weather (Alsobrooks and Townes 2005).

Owners encouraging GPS-based construction see a huge potential for speed, quality, and cost improvements, and they ultimately are in the driver's seat for its adoption. "With the motoring public asking the departments of transportation to deliver projects quicker, this is certainly a step in the right direction," says George Ryan [project implementation engineer, Illinois Department of Transportation (DOT)].

It appears that more owners are writing GPS into project specifications. "Our goal is to have 100% of our jobs machine-controlled" in the next 2 years, says Lou Barrett (head, Minnesota DOT computer engineering team). Those who are less ambitious are at least starting to address GPS in project manuals, should contractors choose to use it (Hampton 2005).

The investment in high-technology surveying equipment has helped the California DOT (Caltrans) dramatically reduce design and construction support costs over the last 30 plus years. Between fiscal year 1971–1972 and fiscal year 2004–2005, the number of persons onboard in field surveys decreased from 898 to 509. Over the same period, the percentage of field surveys of persons onboard to capital outlay support workload dropped from 14.4% to 5.5%.

Over the last decade, Caltrans has spent approximately $10 million (an average of $1 million per year) on high-technology survey equipment, including GPS and robotic total stations. Over that same period, the percentage of field surveys staff to capital outlay support workload has dropped from approximately 7.5% to 5.5%, or 0.2% per year. The increased productivity has allowed surveys to free up staff and resources to begin to eliminate the historical monumentation backlog and other project close-out work. High technology has also enhanced safety for surveys staff and the traveling public. The ability to perform surveying operations away from traffic has reduced the number of lane closures (G. Mallette, personal communication, May 25, 2006).

EXTENT OF USE

One-quarter of the respondents reported no experience with GPS technology and another quarter have experience with fewer than a dozen projects. The remaining agencies are split, with varying levels of experience with GPS in delivery of their projects as shown in Table 3 and Figure 23.

Table 4 and Figure 24 represent survey responses of GPS application use percentages by agencies, consultants, and contractors. Table 5 shows agency satisfaction levels for applications. It was assumed that contractors dominate the machine guidance application and the responses logically reflect similar domination in GPS layout and staking. Both contractors and agency personnel reported almost equal application of GPS for structure locations, whereas the agencies reported significantly greater use of the technology for pay quantity measurement and documentation.

When agencies were asked what types of base station networks are used in their GPS activities, the responses show in Table 6 a one respondent difference between CORS and the High Accuracy Reference Network as the most prevalent.

REPORTED BARRIERS TO IMPLEMENTATION

Table 7 displays agency opinions regarding factors that restrict the use of GPS technology in the delivery of construction projects. The most significant barrier to implementation cited was lack of agency specifications regarding GPS use. The next most popular responses were agency lack of GPS equipment, a lack of knowledge concerning the benefits that GPS can provide the construction delivery process, and inadequate user technical skills. Budgeting and agency procedural issues had a significant number of votes along

TABLE 3
QUANTIFIED GPS RESOURCE SAVINGS

GPS Application	Replacing	Quantified Savings
Grade checking	Manual method	Up to 66% time savings
Reduction or elimination of stakes	Conventional staking	Up to 85% time savings
Improved material yields/select fills/undercutting	Overruns using manual methods	3% to 6% by volume
Uninterrupted earth moving production—All weather continuous shifts (including night work)	Day shifts, nonprecipitous weather	30% to 50% time savings
RTK (robotics stakeout)	Traditional survey stakeout	More than 100% in speed and 66% in staffing (labor count)

RTK = real-time kinetic.

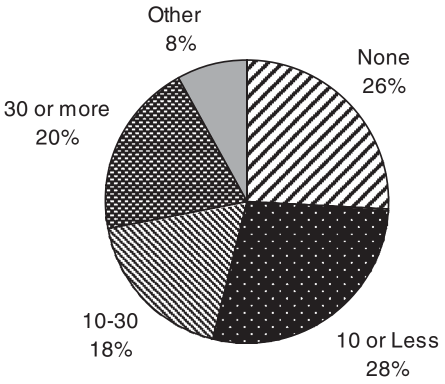


FIGURE 23 Agency GPS usage by number of projects.

TABLE 4
AGENCY GPS UTILIZATION 2005

Project Count	No. of Responses	Response Ratio
None	12	25%
10 or less	13	27%
10–30	9	19%
30 or more	10	21%
Other*	4	8%
Total	48	100%

*Other responses:
1. Not available.
2. One project on contractor grading equipment.
3. Not specified in contract, yet contractor can use.
4. Approximately 100 to 200.
5. GPS is not specifically called for in Ohio DOT specs.

with issues concerning the agency and consultant design function.

Collected literature revealed that the lack of 3D terrain models is a significant barrier to GPS machine guidance. The majority of design engineers issue 2D paper drawings to contractors. To exploit the greater benefits of GPS, the drawings must be in digital 3D formats. Case studies from the literature reveal that in most instances contractors are creating the 3D terrain models themselves when accommodating design engineers allow them access to their 2D digital terrain files. This is reported to be a laborious and expensive process (although still cost-effective on large enough projects) for the contractors. This requirement has spawned a market for consultants who specialize in the practice. One such consultant website advertises costs of $500 to $750 (plus additional cost for ramps and intersections) per lane-mile to create the models for GPS use in the field.

Table 8 reveals that only 10 agencies out of 35 reporting address GPS use in their specifications.

The Kentucky Transportation Cabinet reported the following statement in *Transportation Research Circular E-C046* in 2002:

> The biggest challenge is cultural. Many people fear change. If you can show the users how their jobs will be easier or better,

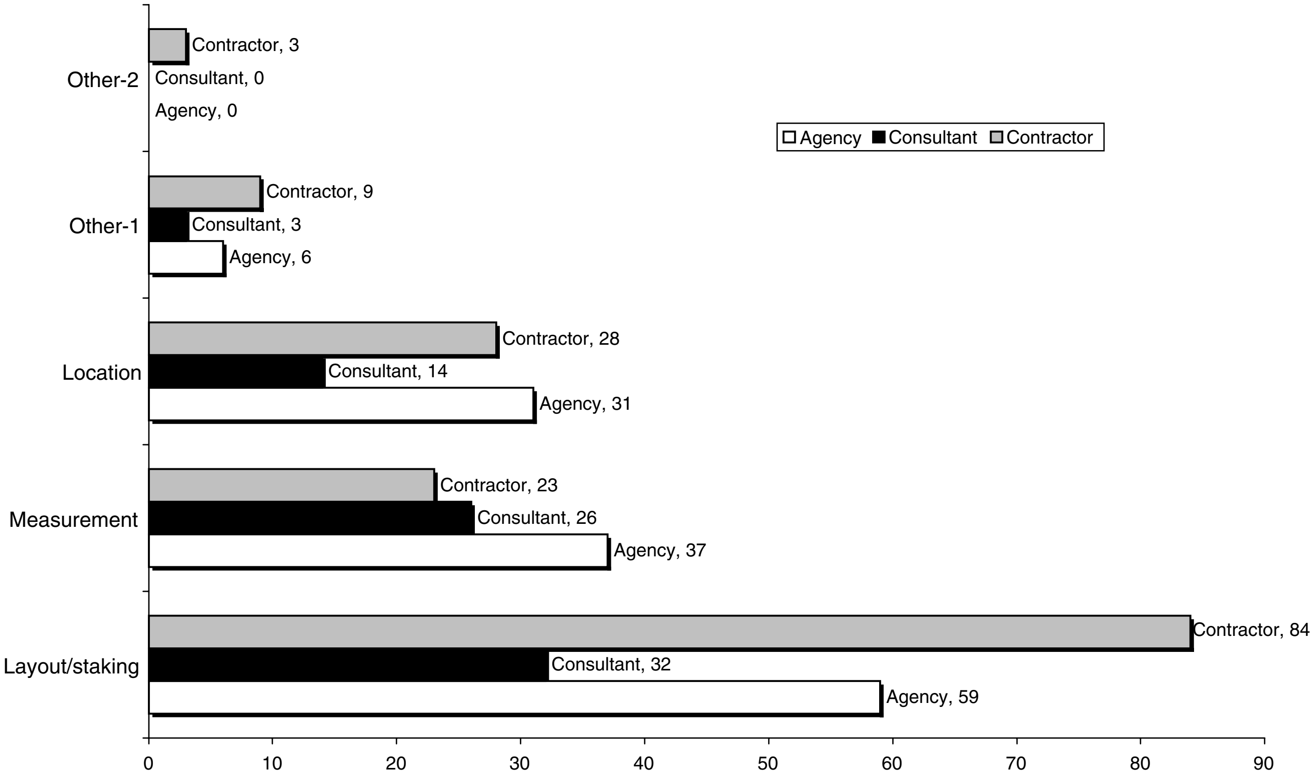


FIGURE 24 GPS application use by project participant (percent by application).

TABLE 5
AGENCY SATISFACTION LEVEL FOR GPS APPLICATIONS

Application	1 High	2 Medium	3 Low	N/A
Layout/staking by agency	45% (17)	24% (9)	3% (1)	29% (11)
Pay quantity measurement	19% (7)	22% (8)	11% (4)	49% (18)
Machine guidance	26% (10)	26% (10)	5% (2)	44% (17)
Utility/drainage location	28% (10)	14% (5)	6% (2)	53% (19)
Inventory tracking	8% (3)	11% (4)	5% (2)	76% (28)
Landscape seeding	3% (1)	3% (1)	8% (3)	86% (32)
Other-1	13% (4)	7% (2)	0% (0)	80% (24)
Other-2	0% (0)	5% (1)	0% (0)	95% (19)

N/A = not available.
Other-1 responses:
1. Layout staking by contractor.
2. Contractors in Montana are using GPS to control grade finishing operations.
3. Establishing survey control monuments for coordinate control.
4. GPS used for control in uninhabited areas.
5. Earthwork: borrow and embankment quantities.
6. Reference station network—CORS.

Other-2 responses:
1. Project layout.

> then most will accept it. The cabinet has a clear commitment to capturing spatial data. The real challenge is in building it so that it can be shared enterprise wide. There is also a high learning curve associated with these technologies. We have to help guide and train the users so that the technology can be more easily incorporated into their work processes. Our constraints have not been from lack of new resources and technologies but have come from the lack of buy-in from project managers in keeping project information updated . . . (Hall 2002).

Software writers are scrambling to update design logic to accommodate the change. Because 3D plans are uploaded into the machines, designers are hindered by software conflicts and a high level of detail required to model a project. “Modeling for machine control is very complex,” says Dean Bowman (director of civil product development, Bentley Systems Inc., Exton, Pennsylvania). He adds: “The sole driver heretofore has been plan sets. People more and more are saying, ‘Hey, we need models!’” Not having 3D models upfront from designers is a major sticking point for contractors. “The barrier to market penetration is this conversion process. You get a digital file, big deal, you still have to build a 3D model,” says Patrick Ruelle (McAninch Construction). And when contractors are forced to build their own digital models, engineers say they lose out on updating their original plans into true as-builts, the “holy grail” of construction documents. Ask civil designers about these hang-ups, and they say that they need more help from software companies. “We saw this coming several years back,” Bowman says, “We are beefing up our modeling capabilities.” Civil software utilities such as Geopak, InRoads, and MX are due for major updates by the end of the year, he notes. That will make it easier for designers to convert 2D plans into machine-compatible, 3D files (Hampton 2005).

TABLE 6
GPS BASE STATION TYPES UTILIZED BY AGENCIES

Base Station Type	No. of Responses	Response Ratio
Do not know	22	61%
CORS	9	25%
HARN	8	22%
Other*	6	17%
NDGPS	4	11%
VRS	3	8%
OPUS	1	3%

HARN = High-Accuracy Reference Network.
*Other responses:
1. WI Height Moderation Program (WI-HMP).
2. Do not use base station network.
3. At contractors discretion.
4. Local base station.
5. We have our own, networks are nearly complete.

MODEL FOR SUCCESSFUL IMPLEMENTATION

Table 9 displays the responses of agency personnel when queried as to the factors that most contribute to successful GPS utilization in their agencies. The most significant trend in the responses is the influence of designer and surveyor roles for contribution to a successful process.

For successful implementation of GPS systems, the following resources and conditions are required:

- GPS equipment;
- Trained personnel for installation, maintenance, and interpretation;

TABLE 7
FACTORS RESTRICTING IMPLEMENTATION OF GPS

Factor	No. of Responses	Response Ratio
Lack of specification (agency)	18	50%
Lack of GPS equipment (agency)	15	42%
Unawareness of benefits (agency)	14	39%
End-user technical skill (agency)	14	39%
Cost (agency budgeting)	12	33%
Procedural issues (agency)	11	31%
Lack of design support	11	31%
Unawareness of benefits (contractor)	10	28%
End-user technical skill (contractor)	10	28%
Conflicting technology standards	9	25%
Lack of GPS equipment (contractor)	5	14%
Other*	5	14%
Legal issues	4	11%
No contractor payment mechanism	2	6%
Network maintenance	2	6%

*Other responses:
1. Need training and software development.
2. GPS data collector.
3. Benefits must be great to change current practice.
4. Accuracy (2).

- Manager or local "champion" to manage and spearhead; and
- Training.

BARRIERS TO OVERCOME

Based on the survey responses discussing barriers to implementation, it would appear that the following are needed:

TABLE 8
AGENCY GPS SPECIFICATION DESCRIPTION

	No. of Responses	Response Ratio
Our agency specifications allow *unlimited* use of GPS during construction	5	14%
Our agency specifications allow *limited* use of GPS during construction	5	14%
Our agency specifications *prohibit* GPS use during construction	0	0%
Our agency specifications *mandate* GPS use during construction	0	0%
Our agency specifications are *silent* on use of GPS during construction	25	71%

- Agencies should plan for GPS development, adoption, and specification creation for both design and construction.
- Agencies should conduct financial studies of cost investment and savings with regard to GPS adoption for budgetary justification.
- Until agencies procure sufficient equipment, they should consider sharing GPS equipment with intra-agency regions, consultants, and contractors.
- Agencies should consider procuring of GPS equipment through construction project pay items. Specification of GPS use on projects could require the contractor to purchase (include in project estimates) equipment for use on the project that becomes agency property at contract completion.
- Agencies should reengineer or adapt the design phase involvement of construction contractors and consultants in the creation of digital 3D project plans. Alternative contractual delivery systems may not be feasible, but constructability review sessions of 3D models may be adopted as a best practice.

Computer-Aided Design Specifications

Among the most significant unresolved issues regarding GPS adoption in transportation agencies (and the industry in general) is that of CAD design practices. Original designs in 3D issued for use by contractors would certainly spur the adoption of GPS machine guidance by contractors. Most designs issued by transportation agencies and consultants today are 2D, requiring that those who wish to leverage GPS's benefits produce the 3D terrain models as an incidental cost of construction.

However, there is a need, even in 2D designs, for a CAD design specification governing the CAD software use and methodology. CAD software uses a "layer" concept in which preliminary and conceptual design objects can be further defined by application of overlapping levels of detail. These levels or layers can be switched into on or off positions (applied or not applied). Typically a design engineer will experiment with alternative designs, stored in layers of the software, before choosing a final design methodology. The result is that a CAD digital plan can have a significant number of layers (sometimes in the hundreds) that do not contribute to the final design. Errors can result when particular layers are omitted or accidentally included when not intended. In addition, developers of 3D models must interact with CAD designs created by different engineers with differing usages of their software layers. A standard and specification for the use of CAD design layers is needed so that designers can derive 3D models more efficiently. The Missouri DOT is experimenting with a second iteration CAD design specification that is friendly to 3D models and GPS.

There are cases in the literature that report on discrepancies between printed-paper 2D plans and digital 3D contract documents. The scenario can occur when paper drawings are

TABLE 9
FACTORS CONTRIBUTING TO SUCCESSFUL IMPLEMENTATION OF GPS

Factor	1 High	2 Medium	3 Low	N/A
Cooperation of surveyors	59% (20)	26% (9)	3% (1)	12% (4)
Cooperation of agency designers	34% (12)	34% (12)	11% (4)	20% (7)
Clear and comprehensive contract specification	9% (3)	26% (9)	26% (9)	38% (13)
End-user training (agency)	21% (7)	21% (7)	24% (8)	32% (11)
End-user training (contractor)	22% (8)	36% (13)	8% (3)	33% (12)
Equipment sharing between agency and contractor	3% (1)	9% (3)	29% (10)	59% (20)
Hardware/software vendor support	26% (9)	40% (14)	14% (5)	20% (7)
Other*	17% (5)	0% (0)	0% (0)	83% (250)

Notes: The percentage indicates total respondent ratio; the number represents actual number of respondents selecting the option. N/A = not available.
*Other responses:
1. We have very little experience with this.
2. 2006, province purchased GPS units.
3. GPS used in preliminary design survey prior to design.
4. Speed and accuracy.
5. (1) sharing of electronic data between agency and contractor; (2) cooperation between agency and contractor to use GPS; (3) cooperation and a common goal within department groups to promote GPS.
6. Efficiency and reduced manpower.
7. Remote structural monitoring of bridge deflection.

printed before final changes in the digital models are made, or when the wrong layer switch is inadvertently omitted or activated. Specifications and directives are required to show which document has precedence over the other.

CAD software vendors foresee the current and future demand for digital modeling. As a result, software vendors will add features and functionality that enhance the modeling delivery methods in future upgrades/versions.

Agency Construction Specifications

- Some state statutes require survey locations (benchmarks) to be set by a registered land surveyor. These statutes and specifications will require review to ensure when and where, and for which applications GPS equipment can be appropriately used (D. Townes, personal communication, July 7, 2006).
- Many prescriptive agency specifications address the method by which the contractor shall lay out and stake the project. Which method(s) will the agency use to check the contractor's staking.
- Quality control guidelines for stakeless construction need to be implemented by agencies and DOTs (Alsobrooks and Townes 2005).
- DOTs need to add machine control as an option in their bid packages (Alsobrooks and Townes 2005).
- DOTs should specify that contractors return paper and electronic "as-built" files when projects are complete (Alsobrooks and Townes 2005).

Fear of Sharing

State DOTs are reluctant to incorporate digital survey data in the contract documents because of:

- Liability fear of misuse or misapplication,
- Procedure for quality control does not exist for stakeless grading, and
- Current methods of 2D plans leave paper trail (Alsobrooks and Townes 2005).

UNEXPECTED OUTCOMES

Paper drawing contract documents are definitely a barrier to achieving the full benefits of GPS technology, based on case studies to date. The entire site plan must be digital to implement GPS. In the private vertical construction segment of the construction industry, Building Information Models (BIMs) are becoming more prevalent. BIMs are 3D CAD (and 4D

CAD) models of buildings. The U.S. General Services Administration (GSA) has a 3-year-old pilot project underway and has developed CAD standards for use on their projects. This would seem to indicate that digital modeling in both segments of the industry will in time become the norm.

- Legal—If digital data (3D models) are used in construction delivery, what constitutes the legal documents defined by legal precedence? If contractors assist the designers in creation of digital plans, what becomes of the traditional implied warranties under United States v. Spearin, 248 U.S. 132 (1918)? Who will be held accountable for design errors?
- Market access—The technology may ban small contractors and subcontractors from being competitive. Costs of GPS hardware and software may be beyond the means of small contracting firms. Some contractors may claim that they do not have personnel capable of interpreting GPS data and information. How do the agencies ensure equal market access to current prequalified bidders and constructors? Should GPS knowledge be a portion of prequalification requirements? The Florida DOT reported that contractors are invited to participate in GPS training workshops that it delivers to its agency personnel. Should there be a GPS certification level requirement for contractors with training provided by agencies?
- Inspection and certification—Processes and methods must be determined at state DOTs, which by statute must engage registered land surveyors in the surveying, mapping, and pay item verification procedures.

CHAPTER THREE

HANDHELD COMPUTERS

DESCRIPTION OF TECHNOLOGY

Definitions and synonyms of HHC continue to be created and altered as differing appliance types converge into handheld size at rapid pace. The product cycle annually introduces new technological devices of increasing utility and power, and of decreasing size and form. For this reason, features and functionality definitions will take precedence over detailed specifications regarding HHCs. HHCs have many names: handheld devices, information appliances, personal communicators, personal digital appliances (PDAs), mobile devices, smart devices, wireless devices, web appliances, and smart handheld devices. An additional name has evolved—pen computers—that refers to devices that use a pen stylus as one form of data input.

For the purposes of this synthesis, Haas et al. (2002) have formulated an excellent definition:

> Handheld computers (HHC) are self-contained electronic devices that fit in the palm of a user's hand and possess, at a minimum, enough computer processing power to surpass the functions of an electronic personal organizer and to run software applications that can extend their built-in functionality. A HHC must be completely self-contained, which inherently implies that some form of user interface must be built in and that no other external devices should be necessary to operate the computer. The above definition excludes most electronic personal organizers that do not have the capability of adding new software that would allow them to function in ways beyond that of a personal organizer. A device that performs only one function may still be considered a HHC. Although on such function-limited devices the user should be able to add her own software application to perform the desired function. In other words, a HHC must also be re-configurable.

HHCs are distinguished from one another by three primary features: form factor, input interface, and operating system (OS) (Haas et al. 2002).

- The form factor of a mobile computer determines its shape and size. HHCs may also be referred to as a Palm-Size PC (personal computer) or a Pocket PC owing to their ability to fit in a user's palm or shirt pocket, respectively. In addition, "form factor" refers to the shape of the computer.
- The input interface of an HHC refers to the method by which data are entered by the user into the computer. There are currently two practical methods of entering data into a handheld PC: (1) through a built-in keyboard or (2) through a touch-sensitive screen. A touch-sensitive screen data input interface can use an HHC's screen as a writing surface for the user (and uses handwriting recognition software). The screen can also display a miniature keyboard on the screen itself that can be used to enter data (most HHCs have both types of input methods). Alternative emerging input methods are voice recognition and miniature, fold-up keyboards that attach to the HHC.
- The OS of an HHC allows it to perform its functions. There are currently several OSs available for HHCs. Although the Palm OS and Windows Pocket PC OS are currently the most popular and widely used, slate and tablet computers have now evolved into handheld form factor size that use the same OSs as full-sized PC. Palm and Microsoft offer several OSs for HHCs. Several manufacturers are using Linux because of its speed on small devices, its configurability as open source software, and its freedom from licensing requirements. The Symbian OS was designed for mobile phones, which are quickly converging into the HHC space.

Hardware

Many HHCs are manufactured with slots that allow for the insertion of different types of accessories such as modems, network cards, and GPS receivers. Hardware specifications typically associated with HHCs include assortments of the following:

- Microprocessor (sometimes energy efficient)
- Video display (usually a digitizer for stylus input)
- Random access memory (RAM) and random onboard memory (ROM)
- Storage media
- Input ports [networking, alternating current (AC) power, microphone, or audio]
- Output ports [Universal Serial Bus (USB), video, infrared, Bluetooth, printer, or audio]
- Ethernet
- Wireless communication [phone or local area network (LAN)]
- Speaker
- Cradle for charging and desktop synchronization
- Battery
- Camera
- Qwerty keyboard

- Stylus pen
- FireWire (1394)
- Hard case screen navigational controls
- Accessories such as carrying cases or belt clip holders
- GPS receiver
- Connections to large-handle trigger devices for scanning
- Connectors for magnetic stripe readers (MSR).

Transportation agencies considering specification of HHCs for use in the delivery of construction projects can choose from products designed for the typical consumer or for industry. Industrialized or "rugged" devices are designed to withstand the elements that are unique to the outdoors and construction jobsites. Owing to the harsh conditions in which computers are subjected by the mobility required of onsite users, Haas et al. (2002) defined the following characteristics that HHCs must possess for effectiveness:

- Attach to a belt;
- Have a long battery life;
- Have a display visible in sunlight;
- Be rugged (i.e., splash, fall, dust, and heat resistant);
- Be easy to operate;
- Fit in the palm of one hand;
- Be multi-functional;
- Have a suitable interface (touch screen or voice recognition);
- Be lightweight so as not to cause fatigue after prolonged use;
- Have sufficient memory;
- Be mobile; and
- Be intrinsically safe, if necessary.

The term rugged computer was coined when referencing industrial strength computer devices for the field (Crews 2004).

> A truly rugged industrial device is engineered, from the ground up, to operate in the most extreme hostile environments. The industrial engineering design is not only limited to the external housing, but includes internal components, special coatings, sealants, and other design features allowing computers to be exposed to extreme humidity, dust, temperatures, vibration, and shock. Included in the mix is a class of products manufactured explicitly for use in hazardous or explosive environments. Understanding the differences between a truly ruggedized computer and an enhanced commercial design can be a challenging proposition for even the most informed customer.

Unfortunately for consumers of rugged computers, there currently does not exist a universal specification addressing HHCs or the industrial market. Industrial manufacturers may specify their products through ratings and standards established by various government agencies, industry organizations, and independent laboratories (Crews 2004). Consumers of industrial class computers would be wise to familiarize themselves with the basics of these standards (see Appendix D). Figure 25 displays various (but not comprehensive) configurations of HHCs.

Software

Software available for HHCs is dependent primarily on the type of OS and the display resolution requirements of the device, and the memory requirements of the software application (same as a conventional desktop computer). Until recently, this has required specialized software programmed to run on smaller devices. HHCs emerging today use a conventional Microsoft Windows OS (the Tablet Edition interfaces with digitizer screen) and can run the same programs as a conventional desktop computer.

HHC software applications are either licensed commercially from a software vendor or created by the user for a specific OS. There are exceptions. Applications developed in Java programming language are usually operable on almost all OSs. Open source software leverages the General Public License and its derivatives, the Internet, and contributions from programmers worldwide to provide (handheld) computer software free of charge, typically for the Linux OS and Java virtual machine language. [The website for a discontinued Linux-operated HHC, Zaurus, by Sharp Electronics, offers more than 2,900 software applications, hardware drivers, and assorted software libraries free for download (http://killefiz.de/zaurus/).] One advantage that software created under the General Public License offers is the access to the program's source code, which the user is legally allowed to alter for specific needs. There are conditions attached to this freedom to create derivative works; they are nonrestrictive, especially for transportation agencies (noncommercial enterprises). One disadvantage of this software development model (open source) is that the programs produced are not typically for niche applications as required in construction delivery.

The functionality of HHCs is expanding at a rapid pace. Technological advances in computing power and the downsizing of hardware components allow the convergence of features previously contained in separate devices into single computers of handheld size. Contemporary features of HHCs include:

- Localized software applications
- Web/extranet applications
- Mobile phone
- GIS/GPS capability
- Sound recording
- Handwriting recording and recognition
- Personal information management
- Text messaging
- Camera
- Cellular radio/walkie-talkie.

Data Input and Output

There are several methods of exchanging data, software programs, and digital files between HHCs and other computer systems:

(a)

(d)

(b)

(e)

(c)

(f)

FIGURE 25 Assorted handheld computers. (*a*) Palm V, (*b*) Sony Clie', (*c*) Cingular 8125, (*d*) Palm Treo 650w Smartphone, (*e*) Symbol STP 1700 Series "Rugged" Pocketable Computer, (*f*) Sharp Zaurus.

- Desktop synchronization: The handheld device is connected by means of a cable (USB or serial) to a second (personal) computer. The second computer (desktop or notebook) may be networked to the Internet, an intranet, or an extranet. Data collected in the field can then be synchronized with the second computer for transfer to other databases or for printing. Software applications for the HHC can be transferred from the second computer onto the handheld for installation into the handheld's OS. Records and other data captured or generated by the HHC can be synchronized into databases on the second computer. This type of scenario relinquishes the features required of the handheld device; that is, wireless network capability, processing power required for larger database and application software.
- Storage media: HHCs are typically manufactured with the capability to exchange data through storage media inserted in several types of built-in card slots. The most common types of standardized slots are Multimedia Card, Secure Digital, Secure Digital Input Output, Compact Flash, and Personal Computer Memory Card International Association (PCMCIA). These media (and their corresponding slots) vary in dimensions, and there are differing types of some; for example, PCMCIA has Types I and II. Cards are available for these slots not only to store and transfer data, but for input functional purposes as well. For example, if your HHC contains a PCMCIA slot, you most likely can find devices that fit the slot to enable GPS, Ethernet network connectivity, or a camera (among others). Many desktop and notebook computers also feature these slots enabling the transfer of data between the devices on storage media cards. Again, this capability can lessen the hardware features required of HHCs when needing to place field data into a central database.
- Wireless networking: HHCs that have wireless networking capability can exchange data and run software applications through the server–client architecture. Many "enterprise" software programs are available that collect data through network browsers on the handheld devices. Once the data are entered, it is stored instantaneously on the network server, relinquishing the requirements of data exchange by means of synchronization or through storage media. These applications can run on the Internet or smaller wireless networks created and maintained by organizations. This method of data exchange is most efficient. Drawbacks to this method are the added cost of hardware and the cost of wireless access service (which may not be available in remote locations).
- Short-range wireless: There are several wireless protocols available currently to handheld devices that allow the transfer of data over short ranges. The two most common are Infrared Data Association and Bluetooth (IEEE802.15.1). The Infrared Data Association uses infrared light rays to exchange data, whereas Bluetooth uses short-range radio frequency. If two devices have an infrared port, and their respective OSs recognize them, this provides a wireless method of data exchange. In this scenario, the devices must be within inches of each other for connections to occur. Bluetooth has virtually the same requirements and limitations; however, its use is less for data exchange than for the use of peripheral devices such as keyboards, printers, and audio devices.
- Electronic mail (e-mail): Some software applications use e-mail capability to transfer captured data to other computers and databases. Wireless networking enables this type of transfer as long as the handheld device possesses a web browser or e-mail client software application. Some devices feature a telephone modem (or one can be purchased for a hardware slot) that enable the user to connect by means of a telephone system to the e-mail server, although these have become less common in the last several years.

BENEFITS OF TECHNOLOGY

The major benefits of HHC technology to the delivery of construction projects is an increase in the organization of field-generated data, a decrease in the cycle time of that data's availability to construction managers, and the decrease in time required for contract administrative duties—formerly known as "paperwork." When data are transferred to digital formats from paper forms, the potential for human error in transfer increases and in general is now an inefficient process. When data are captured in the field and instantaneously reported as information, users can make quick decisions that can avert or minimize problems that would delay or financially harm the project. When field personnel can spend more time in analysis and supervision that previously was spent in contract administrative duties, increases in construction productivity should occur.

Haas et al. (2002) concluded the major benefits of HHCs in construction delivery for contractors to be:

- One-time handling of data in the field.
- Elimination of illogical data entry.
- Completeness of entered data.
- Pens are easier to use for field personnel who are unfamiliar with keyboards.
- Selecting data from predetermined lists speeds up data entry and standardizes the results.
- Data integrity is improved by the elimination of sensitive paper-based recording of data.
- Less storage space for documents is needed because paper documents are not necessary.
- Fewer hard copies of relevant field information are required because they can be accessed on the computer.
- Information may be exchanged wirelessly.

- Updating the HHC's database and recharging its battery is simplified through the use of docking stations ("cradles").
- Electronic measurement instruments can be incorporated into HHCs (e.g., digital tape measures and GPS).
- Field computations are simplified through the use of special software and built-in calculators.
- The HHC can also capture sketches and signatures.
- Users can also view maps and CAD files.
- A help knowledge base can also be incorporated into HHC software to aid field personnel in solving problems and understanding their tasks better.

These benefits must be weighed against the following criteria:

- Ease-of-use
- Dimensions and ergonomics of the HHC
- Functionality of the software and hardware
- Technical overhead required to implement the HHCs
- Impact on the organization's infrastructure (e.g., OSs, hardware, and networks)
- User interface
- Operating system
- Familiarity of the executive decision makers with the HHC
- Initial cost of hardware and software
- Maintenance and upgrading costs of hardware
- Licensing and upgrading costs of software
- Wireless network setup costs and subscription fees
- Cost of in-house technical support
- Training
- Specialist consultant fees
- Integration with project IT systems
- Reengineering of construction processes.

They identified tasks that are well suited to HHC technology:

- Tasks that require access to large amounts of text information.
- Tasks that require viewing a small detail of a document.
- Tasks that require the entry of binary data.
- Tasks that require the entry of data into a form.
- Tasks that require instant transfer of small amounts of information to and from a network.

HHCs have many benefits that can improve construction processes (see Table 10). The most significant benefit is perhaps an HHC's ability to provide workers with real-time access to relevant information at the jobsite, and to send real-time information back from the jobsite to the appropriate decision makers. In addition, an HHC's ability to improve the accuracy of the information being exchanged is one of its primary added values in construction. The type of information and the transmission method are some of the issues that must be assessed during the design of an HHC's evaluation and implementation strategy (Haas et al. 2002).

HHCs have the potential to shift idle and support work time into direct work time. The HHC's access to networks and information, and its ability to interact with the computer on the jobsite, using a form factor that allows the user to walk or be standing either indoors or outdoors, free from wired connections, should eventually prove a significant benefit to the delivery of construction projects.

EXTENT OF USE

The survey questionnaire revealed that of 55 transportation agency responses, 24 agencies (43%) have not implemented HHC technology on any projects. Only 4 agencies (7%) responded as using the technology on all of their projects. Fourteen of the reporting agencies (25%) have implemented the technology on most projects. Table 11 displays agency HHC utilization rates, and provides information regarding agencies that have implemented HHCs on a low percentage of projects or are in the process of testing the technology with plans to implement in the future.

Of the agencies reporting use of handheld technology in construction project delivery, the most widely used application is documentation of daily construction activity by the

TABLE 10
BROAD BENEFITS OF HHC USE

Application	Process Improvement	Resource(s) Saved
Data organization	Time saving for data-administrative tasks	Labor count, man-hours, project duration, office materials
Data documentation	Real-time (outdoor/jobsite) capture of data closer to source	Labor count, man-hours, project duration, office materials
Data exchange	Time savings as a result of shortened information cycles	Labor count, man-hours, project duration, office materials
Data access	Mobility (outdoor/jobsite) and instantaneous access to project life-cycle information	Labor count, man-hours, project duration, office materials

TABLE 11
AGENCY HHC TECHNOLOGY UTILIZATION ON PROJECTS

Project Count	No. of Responses	Response Ratio
None	21	43%
Used in all projects	4	8%
Used in 10 or fewer	9	18%
Used in most projects when appropriate	10	20%
Other*	10	20%

*Other responses:

- Pilot will be run in six offices in 2006—approximately 60 projects.
- Once per year.
- Pilot project for testing purposes (5 projects).
- California is outsourced—consultant may/may not use HHC.
- Gearing up for trial use on construction projects.
- Used only for communication.
- Currently under trial with two products.
- We have experienced limited use.
- Will be looking into it.
- Used as part of SiteManager.

inspectors. The second-most used application is documentation or tracking of contract working days charged against the contractor—"contract time tracking." The third most significant application of use is the tracking of project materials. The remaining usages by count and percentage are shown in Table 12.

When queried as to which project participants are using handheld technology in specific applications, the responses reveal that more transportation agencies have embraced the technology than have either the project consultants or the contractors (with the exception of GPS and voice communication). The remaining usages by application are displayed in Table 13 and Figure 26.

TABLE 12
AGENCY HHC TECHNOLOGY APPLICATIONS

Application	No. of Responses	Response Ratio
Contract documentation (daily diaries)	23	77%
Contract time tracing	12	40%
Other*	11	37%
Material delivery, tracking, disposition	9	30%
Material testing (QA/QC)	8	27%
Cost tracking	6	20%
GPS location/measurement	5	17%
Construction workmanship (QA/QC)	5	17%
Internet communication	4	13%
Voice communication	2	7%
Radio frequency identification	1	3%
Bar code scanning	0	0%

*Other responses:

- Intranet communication.
- Item quantity entry.
- Laptop for reporting pay quantities.
- Data collectors for surveying functions.
- Data collection for sidewalk defects.
- None.
- Maturity testing.
- None.
- Radio frequency identification submittals, as-builts, reference material, e-mail.
- Material data collector to open concrete for traffic.
- Possible bar code scanning in future.

Table 14 displays the type of field computers used as reported by 44 surveyed transportation agencies. It is most likely that those agencies reporting PDA use are referring to HHC form factor rather than PDA functionality. The term should probably not have been used.

REPORTED BARRIERS TO IMPLEMENTATION

The survey queried transportation agency respondents as to their opinions regarding factors that they believe have hindered HHC technology implementation at their agency. Table 15 displays the results. The most frequent response was the cost of implementation, followed in a tie for second place by software interoperability issues and lack of end-user training. Three factors are tied for fourth place: screens are not viewable in direct sunlight, procedural issues within the agency, and general unawareness of the benefits that the technology can provide.

Based on the survey responses, the most significant barriers to implementation of HHCs are:

- Agency budgetary restrictions—HHC implementation costs can include hardware, software, peripherals, and wireless services such as phone, radio, and the Internet.
- Software interoperability issues—HHC software should be easily integrated with desktop and network applications and databases. Data collected in the field on HHCs should be easily transferable to enterprise-wide databases.
- End-user technical skill/training—Operation of HHCs, although fairly straightforward, may confuse inexperienced users. The survey question should have been divided into two parts; one for hardware training and another for software training. It is possible that most of the confusion lies in the techniques and frustrations of data synchronization between different computers and networks.
- Screens not viewable in direct sun—Consumer grade (nonruggedized) video displays are rarely visible in direct sunlight.
- Agency procedural issues.
- Unawareness of benefits.

Collected literature reveals other possible barriers to implementation of work processes that include the use of HHCs (Haas et al. 2002).

- Human resistance to change—This has been explained as a fear of the unknown, of loosing a valuable asset, and of being unable to adjust to a new technology's demands. This resistance is also explained by a poor understanding

TABLE 13
HHC TECHNOLOGY APPLICATION USE BY PROJECT PARTICIPANT

Application	Agency	Consultant	Contractor	N/A
	(reported percentage/response count)			
Contract documentation (daily diaries)	71% (22)	23% (7)	17% (5)	26% (8)
Material delivery, tracking, disposition	33% (10)	17% (5)	17% (5)	60% (18)
Voice communication	7% (2)	3% (1)	10% (3)	87% (26)
Internet communication	20% (6)	7% (2)	10% (3)	77% (23)
GPS location/measurement	23% (7)	7% (2)	27% (8)	60% (18)
Bar code scanning	0% (0)	0% (0)	3% (1)	97% (29)
Radio frequency identification	3% (1)	0% (0)	3% (1)	93% (28)
Material testing (QA/QC)	33% (10)	20% (6)	10% (3)	63% (19)
Construction workmanship (QA/QC)	33% (10)	23% (7)	10% (3)	63% (19)
Cost tracking	33% (10)	13% (4)	10% (3)	67% (20)
Contract time tracking	43% (13)	17% (5)	10% (3)	53% (16)
Other*	15% (4)	7% (2)	7% (2)	78% (21)

Note: The percentage indicates total respondent ratio; the number represents actual number of respondents selecting the option. N/A = not available.
*Other responses:

- Intranet communication.
- Item quantity entry.
- Laptop for reporting pay quantities.
- Data collectors for surveying functions.
- Data collection for sidewalk effects.
- None.
- Maturity testing.
- None.
- RFIs, submittals, as-builts, reference material, e-mail.
- Possible bar code scanning in the future.

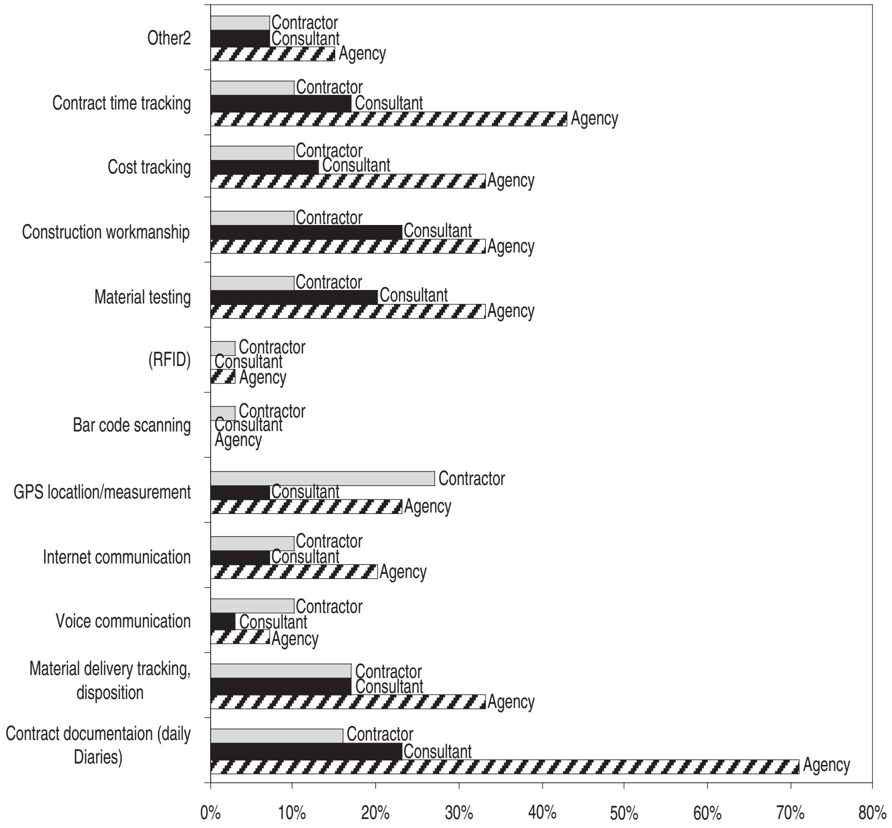


FIGURE 26 HHC technology application use by project participant.

TABLE 14
TYPES OF HHCs USED BY AGENCIES

Computer Type	No. of Responses	Response Ratio
PDA	16	53%
Small notebook computer	11	37%
Slate or tablet computer	9	30%
Other*	8	27%

*Other responses:
- Laptop computer.
- Laptops.
- Currently heavy use of laptops at jobsites.
- Pocket PC.
- Laptop.
- Blackberry for e-mail and phone.
- None.
- Have ordered some slates for testing.

TABLE 15
FACTORS RESTRICTING AGENCY IMPLEMENTATION OF HHC TECHNOLOGY

Factor	No. of Responses	Response Ratio
Cost/agency budgeting	15	52%
Software interoperability issues	12	41%
End-user technical skill/training	12	41%
Screens not viewable in direct sun	10	34%
Agency procedural issues	10	34%
Unawareness of benefits	10	34%
Conflicting technology standards	9	31%
Network/hardware maintenance	9	31%
Other*	8	28%
Hardware durability	7	24%
Slow data transfer/download	7	24%

*Other responses:
- Not robust compared to laptops.
- Multiple efforts.
- Lack of hardware ports for printers, etc.
- All of the above, and administration lethargy.
- Fear of computers.
- Not having a control database system for data.
- Need a central enterprise application for benefits.
- Sync process with SiteManager/SitePad, limited screen size.

of the benefits of change, a poor implementation strategy, and poor labor–management relations.

- Hierarchical organizational structure—Because much of the work on a project is divided between numerous stakeholders who often do not share equal authority or incentives, innovative thinking is dampened as information flows up an organizational hierarchy. This is one of the biggest barriers to adoption of new technology across many industries.
- Lack of IT standards—In addition to the lack of HHC software for construction applications, the construction industry lacks proper IT standards. This may prevent technologies such as HHCs from being successfully implemented, and is possibly one of the reasons why manufacturers of these technologies have shied away from the construction industry.

Haas et al. (2002) also identified tasks that are not well suited to HHC technology:

- Tasks that require computer processing power comparable to that found in desktop computers.
- Tasks that require a “big-picture” view of a document.
- Tasks that require a constant (i.e., always on) connection to a computer network.
- Tasks that require a considerable amount of manual data entry (or writing).
- Tasks that are likely to be performed mostly in direct daylight or under very bright artificial lighting.
- Tasks that actually put work in place.

Their research concluded the following:

- HHCs have potential benefit in terms of time savings and improved information accuracy.
- Achieving benefits from HHCs depends on a proper implementation strategy.
- Time savings at the task and activity levels do not translate directly into time savings at the project level.
- A potential benefit is more likely if HHCs are implemented in multiple activities and projects.
- Several technological and industry barriers must be overcome.
- The marginal benefits of implementing HHCs are greater if the firm has an IT infrastructure in place.

Strategies to Overcome Barriers

The lack of empirical data on HHC performance in construction could be improved through carefully documented pilot projects at construction companies and through controlled experimentation with HHCs under simulated environments. Results from such research could be used to extend and improve the HHC evaluation method presented herein, and to provide practical data for the construction industry and other research efforts in the field. In addition, future research should also address HHC hardware issues that constitute barriers to their implementation on construction projects. The goal of such research should be to identify detailed specifications required for an HHC suitable for use in construction, and to promote more cooperation with HHC manufacturers and the IT industry in general (Haas et al. 2002).

MODEL FOR SUCCESSFUL IMPLEMENTATION

Table 16 displays the responses of agency personnel when queried as to the factors that most contribute to successful HHC utilization in their agencies. The most popular response was that end-user training is a high to medium factor in suc-

TABLE 16
FACTORS CONTRIBUTING TO SUCCESSFUL AGENCY IMPLEMENTATION OF HHC TECHNOLOGY

Factor	1 High	2 Medium	3 Low	N/A
Cooperation/support of vendor/supplier	32% (9)	29% (8)	7% (2)	32% (9)
Comprehensive implementation plan	11% (3)	32% (9)	29% (8)	29% (8)
End-user training	48% (14)	14% (4)	17% (5)	21% (6)
Knowledge of expected benefits	31% (9)	41% (12)	7% (2)	21% (6)
Ease of use	36% (10)	43% (12)	11% (3)	11% (3)
In-house technical support	32% (9)	32% (9)	14% (4)	21% (6)
Other-1	10% (2)	10% (2)	0% (0)	81% (17)
Other-2	0% (0)	6% (1)	0% (0)	94% (17)

Note: The percentage indicates total respondent ratio; the number represents actual number of respondents selecting the option. N/A = not available.
Other-1 responses:

- Field manager.
- Interdepartmental support and cooperation.
- Pilot project for SitePad (module of SiteManager).
- Reduction in number of transposition errors when recording and entering quantity documentation.

Other-2 responses:

- Availability of project contract documents electronically.

cessful implementations. Ease of use was reported as the next most significant factor, followed by vendor/supplier support and agency technical support. Another high scoring factor was knowledge of expected benefits.

Table 17 shows the results of the survey question regarding written HHC specifications. Of 29 responding agencies, 5 reported the existence of a written specification.

An additional comment was included in the open-ended section of the survey questionnaire regarding HHCs:

> Not yet. We are in the process of implementing SiteManager (AASHTO Trns*port module) for contract administrative purposes. Handhelds will become the standard when implementation is completed.

For successful implementation of HHC jobsite systems, the following resources and conditions are required:

TABLE 17
AGENCY SPECIFICATION STATUS REGARDING HHC TECHNOLOGY USE

Written Specification?	No of Responses	Response Ratio
Yes	5	17%
No	24	83%

- Computers enabled with data exchange capabilities (e.g., WiFi, Ethernet, and storage card).
- Network access to project databases (Internet, WiFi-LAN, and synchronization with network-attached desktop computers).
- Software applications specific to the mobile device and its OS (unless browser based).
- “User friendly” or “end-user simplified” implementation plans.

BARRIERS TO OVERCOME

HHCs are valuable as isolated computers that can collect data in the field and then input that data into a database by physically synchronizing to a networked computer. Users can achieve maximum efficiency by connecting HHCs to databases and software application through wireless networks on construction sites. Depending on the location of the projects, this networked environment may prove to be one of the last and most expensive hurdles to overcome before realization. Internet connections, especially broadband, are not currently available in remote locations. Commercial satellite services are available, but may be costly along with wide variances between upload and download speeds.

There currently exists a fragmented commercial market for HHCs. The largest two divisions of the market are between commercial and ruggedized grade machines. After this split is followed, standardization drops off. Machines are designed and marketed for specific industries such as healthcare and manufacturing, each with specific uses sometimes requiring different features and software. Until the construction market can standardize on a set of specifications and features, the cost of specialized "mobile display devices" will remain high (Wood and Alvarez 2005).

As discussed previously, HHCs are manufactured with a variety of OSs, many of which are not capable of communicating with each other or with the OSs used by agency networks. More importantly, software program applications that are written specific to these OSs may not exchange data without added cost and effort. The Extensible Markup Language (XML) has provided a mechanism to solve this problem, but the construction industry has not decisively agreed on standards for this data exchange format. Mobile web-based software applications would go a long way toward solving the problem, but, as discussed, there are current limitations regarding access to wireless networks at all project locations. In addition, the use of web-based software applications would reduce the hardware requirements needed to run them compared with mobile handheld standalone software applications (Wood and Alvarez 2005).

Security is another issue that should be addressed when considering programs involving the use of HHCs. Situations will certainly occur when units are stolen, broken, or lost. Although much of the data generated on transportation jobsites is public information, there may be requirements to store sensitive financial or identification data useful to network hackers and identity thieves. Additionally in the case of accidents, unless there has been a recent upload or synchronization with the network, valuable project data could be lost if not backed up digitally or with paper. Many of the HHCs today offer password and/or thumbprint identification security features.

UNEXPECTED OUTCOMES

Investment in HHCs should be planned very carefully so as to avoid obsolescence. If the computer's features are chosen carefully, agencies can buy machines with a useful lifespan. Input and output features should be useful for the life of the unit; however, changes in software application use (i.e., upgrades) and OSs may require upgrades in microprocessor speeds and memory requirements.

CHAPTER FOUR

AUTOMATED CONCRETE TEMPERATURE TRACKING

DESCRIPTION OF TECHNOLOGY

Automated concrete temperature and maturity tracking is a technique that uses technology for monitoring portland cement concrete while it cures or hydrates in place. Based on the ASTM C1074 maturity method for estimating concrete strength under variable temperature conditions, it can substitute or enhance the existing processes of testing field and lab test cylinders. The following provides background information about this method:

> The maturity method is a technique to account for the combined effects of time and temperature on the strength development of concrete. The method provides a relatively simple approach for making reliable estimates of in-place strength during construction. The origin of the method can be traced to work on steam curing of concrete carried out in England in the late 1940s and early 1950s. As a result of technology transfer efforts by the Federal Highway Administration, there is renewed interest in the method within the United States. The maturity method relies on the measured temperature history of the concrete to estimate strength development during the curing period, when moisture is available for cement hydration. The temperature history is used to calculate a quantity called the *maturity index*. For each concrete mixture, the relationship between strength (or other property of interest) and the maturity index is established beforehand. The strength relationship and the measured in-place maturity index are used to estimate the in-place strength (Carino and Lew 2001).

> Determination of the in-situ strength of concrete is an important step in the quality assurance of an industrial construction project. Typically, cylinder or beam specimens, cast from the same batch of concrete as that used in the construction project, are tested for the in-place strength as they cure. The hydration of concrete, which controls strength development, is primarily affected by two factors: time and temperature of hydration. Due to the difference in placement conditions and the thermal history between test specimens and the actual structure, specimens cast and aged in separate test cylinders can sometimes inaccurately reflect the actual concrete strength within the structure at a given time. The maturity method is an alternative non-destructive testing technology of in-situ concrete (Goodrum et al. 2004).

Three major steps are required to apply the concrete maturity method:

1. *Establish the strength–maturity relationship for the specific portland concrete mix design that will be used in construction*. To accomplish this step, test cylinders should be cast in accordance with normal ASTM procedures. When the cylinders are molded, sensors are embedded in the concrete to record the temperature of the concrete as it hydrates. Temperature readings collected from the sensors are used to calculate a maturity index (maturity-time factor). Equation 1 shows the expression and variable descriptions used to produce the maturity index (Nurse–Saul Material Function).

$$M(t) = \Sigma(T_a - T_0)\Delta t$$

where:

$M(t)$ = maturity index, °C-days (or °C-hours);
T_a = average concrete temperature during each time interval;
T_0 = datum temperature, temperature below which cement hydration is assumed to cease;
Δt = time intervals, days or hours; and
Σ = summation of all the intervals of time multiplied by temperature.

Values for the datum temperature are provided in ASTM C1074. This variable is affected by mix design parameters such as cement fineness, particle size distribution, water–cement ratio, cement type and composition, and initial temperature. After the cylinders are broken to record their compressive strength, their average maturity value is recorded and theses data are plotted against the temperature–time factor. Temperature data are collected from at least two concrete cylinder specimens for a given mix design. Test specimens are broken at typical time intervals of 1, 2, 5, 7, 14, and 28 days, and their average compressive strength and the temperature data from the sensors is used to calculate the maturity index for that particular mix design. Figure 27 displays a plotted strength–maturity curve. Regression analysis can be used to establish the curve.

2. *Estimate the in situ strength of the concrete using the maturity index*. When a concrete pour is done in the field, sensors are embedded within the concrete to transmit temperature information during hydration (typically tied to steel reinforcing). As the embedded sensors or loggers record the thermal profile of the curing structure, the data can be converted to the strength estimation accomplished in the previous step.
3. *Validate the strength–maturity relationship*. Because the maturity method uses time and temperature variables to estimate concrete strength, ASTM requires that the estimated strength be validated before the

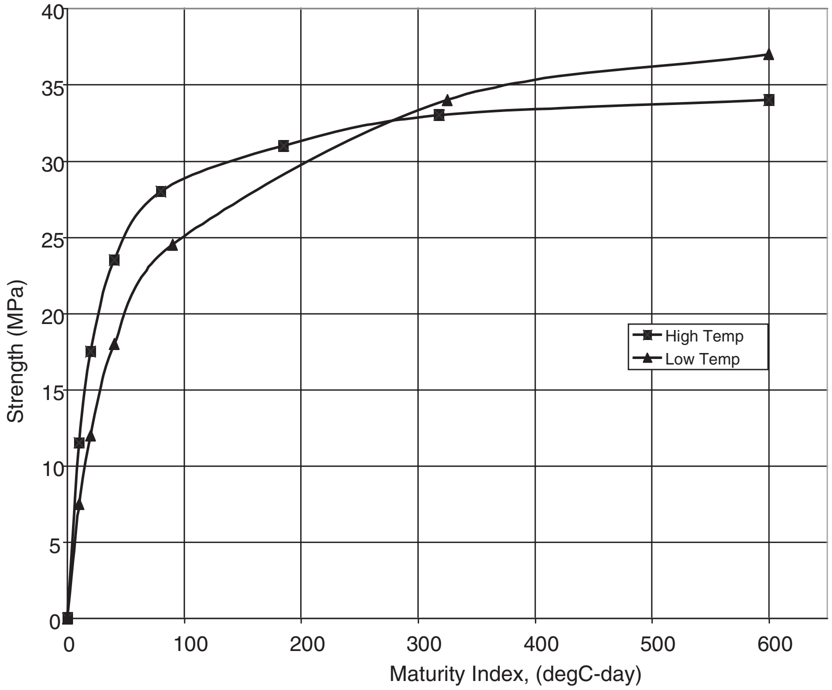


FIGURE 27 Strength–maturity curve.

structure is subjected to force loads, formwork/falsework removal, or post-tensioning. Verification techniques include in-place tests and compressive strength tests on specimens according to ASTM standards.

As long as these steps can be accomplished satisfactorily, any method of acquiring the data is acceptable. Commercial sensors are available that monitor the temperature of the in situ concrete in several forms. Some require that a data collector be attached to their wires, which protrude from a concrete surface. There are microprocessor-controlled data loggers and "smart chips" that wirelessly transmit the data to computers for documentation. The essential hardware components of a working system are as follows:

- Loggers—Logger are sacrificial (expendable) sensors that calculate the maturity index within the structure where it is placed. The system uses sensors that support the Nurse–Saul/or the Arrhenius maturity methods. These devices include memory, a battery, a temperature sensor, a microcomputer, and a clock encased in a 1.5 in. × 1.5 in. diameter cylinder.
- Reader—A reader is used to communicate with and download maturity and temperature data from loggers, typically using an HHC. This device transfers the data to computer application software.
- Software—Software facilitates the downloading of the estimated maturity index and temperature data from the reader into a computer.

Figures 28 through 34 illustrate this process.

BENEFITS OF TECHNOLOGY

Benefits from using this technology include (Goodrum et al. 2004):

- Provides a relatively simple, efficient, and effective approach for making reliable determinations of in-place concrete strength during construction.
- Allows earlier determination of when to remove formwork, apply post-tensioning, or expose a concrete placement to live loads, thereby resulting in accelerated construction cost savings.
- Improves quality control when used in conjunction with, or instead of, testing separately cast specimens to measure concrete strength. This is because the strength estimates from the maturity method are based on data from the actual structure (instead of separate lab specimens).
- Gives instantaneous notification of extreme temperatures or thermal gradients within a concrete structure that may affect quality, thereby allowing remedy or documentation.

Table 18 shoes the road benefits from using this technology.

EXTENT OF USE

Eighty-three percent (39 of 47) responding agencies have used the maturity method on 10 or fewer projects. More than half of the respondents (25) have not used the technology at all. Table 19 displays agency utilization responses from the survey.

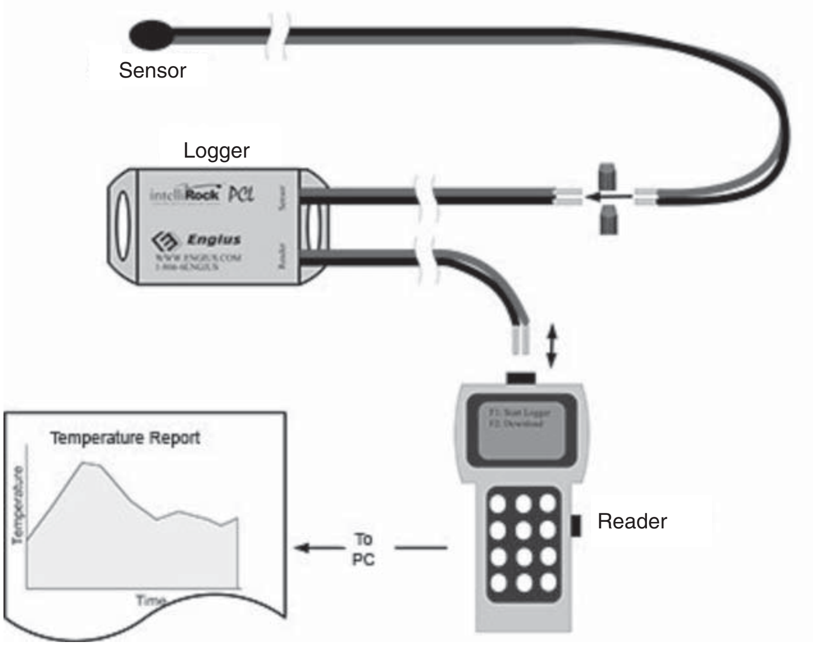


FIGURE 28 PCL System 400 (*Courtesy*: Engius).

FIGURE 29 Maturity meter/reader.

FIGURE 30 Sacrificial logger.

FIGURE 31 Temperature sensor.

FIGURE 32 Sensor/logger encased in test cylinder.

FIGURE 33 Reader visual display.

FIGURE 34 Reader visual display.

Of the agencies reporting use of the maturity method, by far the most frequent construction application is paving, followed by bridge construction as shown by survey responses in Table 20.

Table 21 and Figure 35 reveal that automated temperature tracking and maturity monitoring use by agencies and contractors is approximately equal. Factoring in the consultant's use (under contract to the agencies) gives a slight advantage to project owners for implementation of the technology.

REPORTED BARRIERS TO IMPLEMENTATION

The survey queried transportation agency respondents as to their opinions regarding factors that they believe have hindered automated concrete temperature tracking and maturity monitoring technology implementation at their agency. Table 22 displays the results. The most frequent responses were contract specification issues and a general unawareness of the benefits provided by the technology. An equal number of agencies reported cost and agency procedures to be a hindrance to adoption of the technology.

A barrier to more widespread adoption of the maturity method was the unreliability of conventional maturity meters, which have a history of failure for the following reasons:

- Moisture in the maturity meter;
- Theft of the maturity meter;
- Damage to the maturity meter;
- Battery failure of the maturity meter;
- Sensor wires being severed or otherwise disconnected from the maturity meter;
- Maturity meter malfunction as a result of electrical and/or magnetic interference;
- Chemical discoloration of the maturity meter display cover; or

TABLE 18
BROAD BENEFITS OF AUTOMATED PORTLAND CEMENT CONCRETE TEMPERATURE TRACKING AND MATURITY METHOD

Application	Process Improvement	Resource(s) Saved
Non-destructive and relatively inexpensive PCC in-place strength determination	Allows acceleration of PCC construction task durations	Project and task duration (time)
Enhancement to existing QA/QC methods	Allows acceleration of PCC QA/QC task durations	QA/QC administration time, man-hours
Instantaneous notification of PCC curing abnormalities	Allows acceleration of PCC QA/QC task durations	QA/QC administration time, man-hours, product loss
Data received are from actual structure vs. separated lab specimens	Provides accuracy	Loss ratio

PCC = portland cement concrete; QA/QC = quality assurance/quality control.

- Inability to read the maturity meter's liquid crystal display owing to exposure to sunlight.

Furthermore, conventional maturity meters must remain physically connected to the embedded temperature probes for the entire duration in which maturity readings are desired, exposing them to theft or damage (Case Study . . . n.d.).

MODEL FOR SUCCESSFUL IMPLEMENTATION

Table 23 displays the responses of agency personnel when queried as to the factors that most contribute to successful

TABLE 19
AGENCY UTILIZATION OF AUTOMATED CONCRETE TEMPERATURE TRACKING AND MATURITY MONITORING

Project Count	No. of Responses	Response Ratio
None	25	53%
10 or less	14	30%
10–30	3	6%
30 or more	2	4%
Other*	3	6%

*Other responses:
1. One project this year experimentally as quality control.
2. At the discretion of the contractor.
3. Only one project has substantial use.

TABLE 20
USE OF AUTOMATED CONCRETE TEMPERATURE TRACKING AND MATURITY MONITORING BY CONSTRUCTION TYPE

Construction Type	No. of Responses	Response Ratio
Paving	16	67%
Bridge	10	42%
Structures	5	21%
Other*	5	21%
Noise barrier/retaining walls	0	0%

*Other responses:
1. None.
2. None.
3. Only one bridge project had substantial use.
4. Warping/curling research with university.
5. Concrete intersections.

TABLE 21
AUTOMATED CONCRETE TEMPERATURE TRACKING AND MATURITY MONITORING TECHNOLOGY APPLICATION USE BY PROJECT CONSTRUCTION TYPE AND PARTICIPANT

Application	Agency	Consultant	Contractor	N/A
	(reported percentage/response count)			
Bridge	38% (9)	17% (4)	42% (10)	38% (9)
Noise barrier/ retaining wall	0% (0)	0% (0)	0% (0)	100% (23)
Concrete structure	17% (4)	13% (3)	17% (4)	71% (17)
Paving	44% (11)	20% (5)	48% (12)	32% (8)
Other	4% (1)	4% (1)	0% (0)	92% (22)

The percentage indicates total respondent ratio; the number represents actual number of respondents selecting the option. N/A = not available.

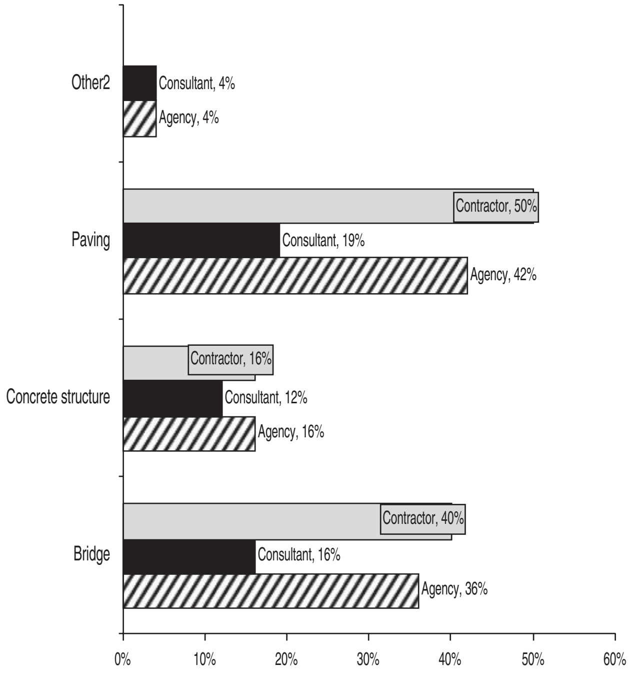


FIGURE 35 Automated concrete temperature tracking and maturity monitoring technology application use by project construction type and participant.

TABLE 22
FACTORS RESTRICTING AGENCY IMPLEMENTATION OF AUTOMATED CONCRETE TEMPERATURE TRACKING AND MATURITY MONITORING TECHNOLOGY

Factor	No. of Responses	Response Ratio
Contract specification issues	9	45%
Unawareness of benefits	9	45%
Cost/agency budgeting	6	30%
Agency procedural issues	6	30%
Other*	4	20%
End-user technical skill/training	3	15%
Conflicting technology standards	2	10%
Sensor placement	1	5%
Software interoperability issues	0	0%
Network/hardware maintenance	0	0%
Data acquisition	0	0%

*Other responses:
1. None.
2. Concern of supply of consistent concrete mix.
3. Can be used at the contractors discretion.
4. Familiarity and being comfortable with the change.

automatic monitoring of concrete temperature and strength by use of the maturity method in their agencies. The two most highly rated and chosen factors were ease of use and knowledge regarding the benefits of using the technology. Table 24 shows how many agencies have established specifications regarding this process.

The intelliRock system uses an embedded microprocessor with a high-precision temperature sensor to measure temperature and calculate maturity in real time with no permanently affixed external devices. The embedded microprocessor and sensor (called a "logger") is placed into the concrete structure and then activated using a handheld reader. The reader is then disconnected, leaving only two lead wires protruding from the concrete. Whenever a strength measurement is desired, the handheld reader is simply reattached to the two wires and the current temperature and maturity is displayed. In addition, users can review and download a history of temperature and maturity values and time-stamped minimum and maximum temperatures in a secure, unalterable format (Case Study . . . n.d.).

In addition to scheduling advantages, the intelliRock system added a new dimension of quality control to the project. Based on methods pioneered by the Texas DOT, periodic destructive testing results were compared with the strengths predicted by the maturity method. Any discrepancy could indicate an unintentional change in the concrete mix provided to the jobsite. However, engineers on site were impressed with the across-the-board agreement between the cylinder break strength and the strength predicted by the intelliRock system.

For successful implementation of automated concrete temperature tracking systems, the following resources and conditions are required:

- A plan for sensing deployment,
- Backup procedures in case of data logger failure,
- Site accessibility and power, and
- Commitment at all levels of site personnel.

BARRIERS TO OVERCOME

In 2005, FIATECH identified the following issues with wireless sensing devices and networks (Wood and Alvarez 2005):

- Sensors are capable of generating very large volumes of data; modern sensor systems could easily overwhelm conventional database storage and processing systems. Distributed data storage and processing are critical to the functionality of modern sensor systems. Currently, researchers are working on embedding software into sensors to make them more selective about what data to transmit to base and to condense information to conserve power and storage space. Without that capability, large sensor networks could quickly overwhelm themselves and back-end computers by draining bandwidth and battery power while trying to transmit a flood of data from the field.
- Building networks of sensor systems requires overcoming many challenges. Much of what is taken for granted in desktop computing is at a premium in wireless sensor networks. The individual nodes are incredibly resource constrained. They have limited processing speed, storage capacity, and communication bandwidth. Their lifetime is determined by their ability to conserve power. All of these constraints require new hardware designs, software applications, and network architectures that maximize the nodes' capabilities while keeping them inexpensive to deploy and maintain.
- Much of the data generated and communicated by sensor systems is sent wirelessly to the network. This requires a secure network that will not allow hackers to gain access to proprietary information. The companies that supply wireless sensor networks have security protocols built into their sensors.
- Interference issues for sensor networks are the same as for any radio frequency device. Large metal objects and concrete walls will block the signals. Wireless network companies have tried to remedy this situation with self-healing sensor networks; when one sensor fails, it automatically finds the next sensor to transfer its information.

TABLE 23
FACTORS CONTRIBUTING TO SUCCESSFUL AGENCY IMPLEMENTATION OF AUTOMATED CONCRETE TEMPERATURE TRACKING AND MATURITY MONITORING TECHNOLOGY

Factor	1 High	2 Medium	3 Low	N/A
Cooperation/support of vendor/supplier	13% (3)	38% (9)	8% (2)	42% (10)
Cooperation/support of contractor	24% (6)	28% (7)	12% (3)	36% (9)
End-user training	17% (4)	42% (10)	4% (1)	38% (9)
Knowledge of expected benefits	35% (9)	31% (8)	4% (1)	31% (8)
Ease of use	40% (10)	24% (6)	0% (0)	36% (9)
In-house technical support	16% (4)	40% (10)	4% (1)	40% (10)
Other-1	14% (3)	0% (0)	0% (0)	86% (18)
Other-2	6% (1)	0% (0)	0% (0)	94% (17)

The percentage indicates total respondent ratio; the number represents actual number of respondents selecting the option. N/A = not available.
Other-1 responses:
1. Early opening of pavements to traffic.
2. This technology is in the trial phase at this time.
3. Project delivery.
4. Specifications.

Other-2 response:
1. Early form removal for bridges and early traffic placement for pavement.

- The lack of industry standards has complicated the sensor integration process, inhibiting broad-based deployment. Any given facility is currently an amalgamation of several different manufacturers' products. Sensors from different suppliers often are unable to work on the common networks, because of proprietary data models or communication protocols. Although sensors continue to gain intelligence, all too often they remain "mute," unable to communicate their data to other information systems. Ownership of these proprietary data models and communication protocols are often crucial to the business strategy of technology suppliers. The willingness to integrate and use open protocols challenges the traditional, competitive advantage goals of technology companies. Universal and open communication standards are needed to enable industry-wide interoperability and improved efficiencies. To fully utilize sensor systems, the challenge is standardization in instrument-level network architecture and software object models.
- A major issue for wireless sensors is power. To be truly wireless, the sensor needs a local power source. Currently, there are a few options available: battery power, solar power, and electromagnetic vibratory power. These power sources need to be reliable so that the sensor can communicate effectively.

TABLE 24
AGENCY SPECIFICATION STATUS REGARDING AUTOMATED CONCRETE TEMPERATURE TRACKING AND MATURITY MONITORING TECHNOLOGY USE

Written Specification?	No. of Responses	Response Ratio
Yes	10	40%
No	15	60%

UNEXPECTED OUTCOMES

Burcu Akinci of Carnegie Mellon University discovered the following in the course of her research in sensing technologies related to active project quality control (Akinci n.d.):

- *Planning for sensing deployment*: Soon after we started deploying these technologies, we realized that it is inefficient to fully saturate a built environment with embedded sensors and laser scanning activities. It is important to identify ahead of time what types of sensors should be utilized when. Many issues, such as modality, location, time and duration of sensing, as well as data communication and storage, should be considered in a sensing plan. Due to the dynamic nature of construction projects, sensor planning is a major problem.

- *Silent failures of data loggers*. There were two major issues about data loggers associated with these sensing systems. First of all, the allocated memory was not sufficient to handle all the data that was to be collected for active quality control. This current limitation in the memory size of data loggers further emphasizes the need for planning for sensing deployment. Moreover, in many cases, the data loggers failed silently when the allocated space filled up. As a result, when deploying some of these systems on construction sites, one might think that the data [are] being captured, only to find afterwards that the data logger was full and did not record anything after a certain point in time.
- *Applicability on the site*: The size of the equipment used and its setup impacts the mobility of the equipment on the site. In certain cases, the equipment was not sufficiently mobile or ruggedized for the full range of construction site conditions, such as mud and non-compacted ground. The need for power is still a problem when it is not available on a site at a given point in time. The accessibility of the locations that are optimal for using these sensing technologies is sometimes a problem. Finally, wires also create major problems on construction sites. In certain cases, even the wireless sensors still require a bit of wire in their setup.
- *Commitment at all levels of site personnel*. Experiences showed that to be able to get the most out of these technologies, all site personnel from top management to field workers should see the benefits and should be committed to or supportive of using such technologies on the site. Otherwise, the benefits of using such technologies are not fully realized.

Sensor networks raise security and privacy issues that require collaboration between engineers, social scientists, legislators, and policymakers for solutions. When wireless networks are implemented, wireless sensors will generate a lot of data that are not seen today. Security is important to keep these new data on the wireless network away from unauthorized users. This will bring up privacy issues when security systems capture personal data (Wood and Alvarez 2005).

CHAPTER FIVE

FOUR-DIMENSIONAL COMPUTER-AIDED DRAFTING MODELING

DESCRIPTION OF TECHNOLOGY

Traditionally, architects and engineers have expressed their design intentions to contractors and other project stakeholders through 2D paper-media contract drawings developed as part of the contract documents. The contract specifications provide an additional medium to communicate product and process details that are too extensive for paper drawing notes. Additionally, it is common for designers and builders to develop scaled physical models to visualize the as-built product. These physical models have proven beneficial to all the major project participants (e.g., owners, designers, and builders) not only in their ability to allow visualization of the future completed facility, but also the opportunity to test aesthetic preferences, component building systems, and spatial relationships of external entities surrounding the proposed facility. Design prototyping in the vertical construction industry also typically includes physical mock-ups for the testing of building system component compatibility, material fabrication, etc. (Gopinath and Messner 2004). Over the last 20 years, with the advancement of computer technology, CAD has enabled the efficient production of 2D construction contract drawings.

During the past decade, CAD software applications that enable production of designs in three dimensions have become increasingly mature. The use of 3D CAD implementation of the (*z*) coordinate to 2D CAD's (*x*) and (*y*) coordinates allows for the plotting of quantitative data in 3D space (although still viewed in a 2D surface). When three or more coordinates are connected in a 3D space, surfaces and volumes of the design can be visualized. These techniques are referred to as 3D objects or 3D models, which allow 3D information displays of quantitative data and virtual space (Issa et al. 2003; F. Shiratuddin, University of Mississippi, personal communication, June 1, 2006).

4D CAD consists of a 3D CAD model with the added dimension of time (in its simplest form). The time element typically consists of a Gantt chart, critical chain, or critical path method construction work schedule. Linking schedule activities to components in the 3D model allows for sequential visualization of the construction design plan. 4D CAD models, which typically refer to 4D CAD plus additional datasets and features such as estimates and virtual reality (VR), allow project stakeholders to visualize, measure, and quantify direct components and spatial relations of the facility included in the design, as well as visualize the time-lapsed construction sequence. These capabilities are available very early in the facility life-cycle process.

An important distinction is the difference between simulation and VR. Although there is no universal definition of VR, 4D CAD is always a simulation and can be VR. Simulation is defined as:

- Imitation or representation, as of a potential situation or in experimental testing (*The American Heritage Dictionary* . . . 2000);
- Representation of the operation or features of one process or system through the use of another;
- A mathematical exercise in which a model of a system is established, then the model's variables are altered to determine the effects on other variables (Scott 2003); or
- The technique of representing the real world by a computer program; a simulation should imitate the internal processes and not merely the results of the thing being simulated [WordNet(r) 2.0 2003].

VR has been defined as meeting the following four criteria (T. Sulbaran, University of Mississippi, personal communication, June 6, 2006):

- It must be computer generated.
- It must provide 3D visualization (clues).
- The user must have the ability to navigate through the simulation and interact with the environment (i.e., changing perspectives and views).
- The simulation must occur in real time.

It has also been defined simply as "the suspension of disbelief" when viewing or imagining something which is not real (D. Fletcher, University of Mississippi, personal communication, May 25, 2006).

Unless specific software applications are used, 4D CAD will only simulate the building sequence, although that in itself has tremendous value. Currently, the volume of academic and industrial research conducted in the areas of VR and BIM causes difficulty in separating them from 4D CAD. VR and BIM will be discussed in chapter seven.

There are two primary software applications (modeling tools) required to produce 4D CAD capability:

- *3D CAD application*: Software that encapsulates the "object-oriented" CAD model should contain the entire scope of project design data.
- *Scheduling application*: There currently exists an eclectic set of available scheduling applications that vary by feature, price, and licensing. The construction activities contained in the project schedule are linked, through the coupling module, to design objects in the 3D CAD model.

Additional software applications that may be required are:

- *Coupling module/application programming interface*: An application programming interface is the interface that a computer system, software library, or software application provides to allow requests for service to be made of it by other computer programs and/or to allow data to be exchanged between them (*Wikipedia* 2006). This tool acts as a "junction box" that ties data structures and program functions together between the other three applications. It acts as the interpreter of the differing computer languages and data structures.
- *Simulation and/or simulation viewer application*: Typically, the visualization can be viewed through the 3D CAD application in time-lapse sequences determined by the schedule application. Visualizations desired beyond the basic schedule sequencing will require additional software applications.

When these tools are properly coupled and synchronized, the result is a 4D CAD project model. This product then allows simulated visualization of the design model's intentions according to the scheduling application's timing and logic. The viewer can see the facility's construction components evolve in time-lapse into the completed product.

Some commercial products have emerged that encapsulate all required software functionalities to produce 4D CAD models. These suites interface with most popular commercial 3D CAD applications. Many of these all-in-one 4D modeling applications have originated from academic research and the growing service industry that 4D CAD has spawned (consultation and assistance in development of the 3D and 4D models). As often happens with information technology tools, personnel who have the knowledge and expertise can develop their own tools in-house. It is often more economical to purchase these applications from commercial vendors than to finance their creation, depending on the level of complexity desired. One of the most expensive components of developing 4D CAD is the creation and linkage of the 3D model to the schedule.

Hardware requirements consist of computers with fast processing and graphical rendering capability. Optimization of these computer processing features necessitates components such as large capacities of RAM, fast microprocessors, and state-of-the-art video cards. With the popularity of computer gaming and the current availability of dual processor motherboards, video cards and processing speed should become more affordable with time. In addition, the availability of microprocessors with 64-bit processing functionality is becoming widespread and should aid processing speeds. Large capacities of storage media is also a requirement as the models and datasets are typically measured in gigabytes (Sheppard 2004).

BENEFITS OF TECHNOLOGY

Material Fabrication and Procurement

The process of developing 3D and 4D models, with early involvement of collaborative project stakeholder teams, lends itself well to projects with fabrication-intensive materials and equipment requirements (see Table 25). The emergent philosophy of Lean Construction encourages the use of 3D modeling with emphasis on reducing lead time for engineered-to-order products, incorporation of cost modeling, integrating product and process design, and supply-chain management (*LCI Research* n.d.).

Constructability Review

Construction project constructability reviews are "peer-review" sessions of a project's design intentions. Various project stakeholders review the design to add perspective on construction efficiency and effectiveness, suggest changes in relation to cost-effectiveness and assembly relationships, and value engineer major component parts of the design. 4D CAD is an effective tool for this purpose. Not only does it force the stakeholders to collaborate early in the manufacture of the required 3D model, but the visualization of the sequential building process illuminates material staging and fabrication issues, spatial requirements not easily detected without visualization, and reveals conflicts, errors, and inconsistencies in the planning stage.

Detection of interferences during the design process provides opportunities for quality assurance in the construction phase (i.e., on site) (Gao et al. 2005).

Communication of Building Methods and Systems

Case studies have proven 4D CAD models to be the most effective system to date that communicates the design intention to all project stakeholders. The ability to visualize sequential planned construction operations allows project participants to consider (experience) constructability issues that can only be imagined (from prior experience in similar situations) using 2D tools. Most case studies emphasize the benefit of spatial analysis regarding avoidance of trade stacking, equipment placement, material fabrication and staging, and site organization. The phenomenon has been referred to as execution space (Heesom and Mahdjoubi 2004). In applications

TABLE 25
BROAD BENEFITS OF 4D CAD MODELING USE

Application	Process Improvement	Resource(s) Saved
Material fabrication and procurement	Can occur before construction phase	Lead and waiting time, project duration
Constructability review	3D versus conventional 2D, can evaluate spatial limitations and challenges	Change order count, project duration
Communication of building systems	Effectiveness	Collaboration time, physical mock-ups
Quantity tracking	Reduction of paper documentation, instantaneous	Data entry iterations, information cycle time
As-built documentation	Reduction of paper documentation, instantaneous, organization/sole source of data	Data entry iterations, information cycle time, loss of as-built data capture
Public relations	Effectiveness	Presentation time, logistics, physical mock-ups
Schedule optimization	Reduction of omitted activities and logic error	Scope problems, change order count, project duration
Incidental project resource requirements	Reduces imagination and dependence on experience required during normal planning operations	Project delays caused by inadequate resources
Change management	Design changes can be experienced virtually before physical construction implementation	Strategic project design and planning duration

to transportation facilities that are commonly constructed under traffic use, the project phasing can be designed while a series of scenarios are visually analyzed, because traffic count can be an included dataset of the 4D model. If sufficient detail is included in the model, the driver's perspective can be simulated or experienced through VR. This is an incredible design and planning advantage because planners can adjust roadway and bridge elevations for maximum driver safety. In addition, the visualization of the phasing from the drivers perspective can aid planners in the design and placement of traffic control and maintenance devices, permanent and temporary signage, and other safety features. It has been proposed that database object libraries be created (standards) for use in 4D models specific to these highway and traffic elements (Liapi 2003).

Quantity Tracking

When modelers develop 3D CAD models, they typically embed building objects with quantity data. When these objects are linked to construction activities in a schedule, quantity information is made available to the 4D model. When the quantity data contained in the 3D models is associated with construction activities in the 4D model, it is easy to produce quantity surveys of a facility's components. The 4D model allows comparison of as-designed, as-bid, and as-built material and component quantities. This fringe benefit of the modeling process, which is currently time intensive and costly, should be considered as "debit" cost, and subtracted from the normally time-intensive estimating process of the project delivery life cycle.

As-Built Documentation

4D modeling allows the user to shift time in the proposed construction work plan either forward or backwards. This ability, given that the scope detail is sufficient and that the component quantity datasets are a part of the model, allows the potential of documenting as-built quantities by declaring the percent complete of either tasks (as is typically done in 2D schedules) or facility components. Fischer and Liston (2001) describe separate schedules and models for as-built, as-planned, as-revised, and as-proposed projects. With the ability to set a baseline construction work plan, users could track as-built quantity variance from as-designed and as-bid work plans. Smith (2001) discusses the potential of capturing as-built data in the model to serve for information and knowledge throughout the operations and maintenance stages of the facility life cycle.

Public Relations

4D CAD has been widely reported to be a valuable tool in expressing design intentions and construction sequence plans to individuals not familiar with visualizing from 2D media. For transportation agencies, the use of 4D CAD can effectively communicate the phasing or staging sequences of projects that are long in duration and complex in relation to 2D visualization.

Schedule Optimization

From the case studies collected in a literature search of building construction, a common reported benefit is the identification of omitted schedule activities. By visualization of the work progress, missing activities become apparent.

> One of the major improvements over earlier applications is the ability within Schedule Simulator to automatically pass changes to the information in the scheduling program to update the 4D model. This allows you to try many different options before committing to a particular model or schedule (Smith 2001).

Incidental Project Resource Requirements

The simulations visible as a result of 4D CAD models are a function of the datasets included in the model. Because designers and constructors have differing perspectives of the same project (model), it is understandable that each would optimize the model from their own viewpoint. The designer's contribution of the 3D model emphasizes design components, and the constructor's schedule emphasizes the application of the design intention. From the case studies reviewed, the missing model elements revealed by the 4D model simulation are typically incidental project resource requirements that are beneficial to both perspectives. These omitted resources tend to include items such as scaffolding, falsework, temporary traffic control devices, and other items not contained in the direct design components or specifically defined as a scheduled work package. The ability to visualize construction tasks at the operations level, in context of their spatial environments, has also proven beneficial as an aid to constructors in specifying their task resource requirements. As stated,

> 4D CAD can depict the evolution of the construction product but not the interaction of the resources that build it . . . operations visualization therefore differs significantly in concept, content, and usage when compared to 4D CAD (Kamat and Martinez 2002).

Improved Change Management

Possessing the capability with a 4D model to visualize (and experience) the impact of design changes in the construction delivery stage of a facility enables users to make strategic design decisions earlier than with the traditional process of 2D constructability reviews. Every case study encountered in the literature review reported significant reductions in change orders and constructor information requests to the designers. When the constructors are involved early in the model creation (planning) and analysis, the team is empowered with the capability to run "what-if" scenarios and almost instantaneously evaluate the ramifications of the episode. Typically this exercise results in the discovery of errors and omissions, both in the design and schedule elements of the models. Making, identifying, and correcting the mistakes in simulated construction or VR has reduced their occurrence in actual construction project delivery.

EXTENT OF USE

4D CAD modeling currently is not significantly utilized by transportation agencies according to the synthesis survey responses. Of 47 transportation agencies responding to this section of the questionnaire, only 5 indicated experience with 4D CAD modeling. Table 26 is a summary of the responses.

Table 27 displays the small sample of respondents that have experience with 4D CAD. The driving application would appear to be communicating construction project plans to the public. Construction delivery-related applications have some use, whereas quantity tracking has none.

Table 28 and Figure 36 display 4D CAD application use by project participant.

Table 29 reveals the project procurement methods in which 4D CAD has been used by respondents.

REPORTED BARRIERS TO IMPLEMENTATION

Cost

Costs and return on investment are always determining considerations when contemplating investment in technology, especially technology that disrupts status quo business processes. 4D modeling for construction delivery is the perfect application of the statement. The costs for using it include software licensing and hardware purchases, service costs of outside consultants if used for model creation or assistance, training, and in-contract salary costs of the model-building collaboration teams required at the outset. The total project cost percentage normally expended in the design development stage will increase substantially when 3D and 4D models are central to the project's strategic planning. Currently, in this early-adoption stage of the technology's history, the significant costs enable only large projects to absorb them.

TABLE 26
AGENCY 4D CAD UTILIZATION

Project Count	No. of Responses	Response Ratio
None	39	83%
10 or less	3	6%
10–30	1	2%
30 or more	1	2%
Other*	3	6%

*Other responses:

1. Not used.
2. We use 3D and 2D CAD in all our work.
3. I dont know.

TABLE 27
AGENCY 4D CAD APPLICATIONS

Application	No. of Responses	Response Ratio
Public relations	4	67%
As-built documentation	2	33%
Constructability review	2	33%
Material fabrication and procurement	1	17%
Other*	1	17%
Communication of building methods/systems	0	0%
Quantity tracking	0	0%

*Other response: We do not use.

The most expensive variable discovered in the literature review was the cost of the time investment required for model creation and participant collaboration:

> Benefits need to be weighed against the time investment to build models . . . spent over 300 man-hours building a 3D model of Bay Street, primarily because only 2D CAD data [were] available. But we'll recoup it in time savings (Roe 2002).

The return on investment has been well documented in project case studies conducted on vertical building projects. There is evidence that, in building construction, the technology can save, at a minimum, between 4% and 6% of the total project cost (*Emerging Technology for Design and Construction* 2005). The case studies have also revealed that project teams become more efficient in applying the process with successive iterations of projects completed involving the technology, thus lowering costs (Sawyer 2005). Further research would be beneficial involving total cost studies of such projects and determination of cost–benefit ratios to contract size. All of the case studies gathered in the literature review were consistent in that money expended upfront in the process resulted in savings during the construction delivery stage.

> One of the largest barriers to implementation (at least in the conventional AEC industry) is that 4DCAD technology requires engineering designs as 3D models, something currently uncommon. From 75 to 80 percent of a 4D model's cost involves creation of the underlying 3D model. When the design team works in 3D, that cost becomes a project benefit. Model costs on large projects might run as low as one-half a percent of the project budget, yet be returned 50 to 100 times over in project savings. However, if project participants don't clearly establish a 4D model's scope and purpose and level of detail prior to its modeling, the cost-benefit ratio decreases (Sheppard 2004).

Software Interoperability Issues

As stated earlier, the current primary cost driver of 4D CAD modeling is the production of digital models. Dependent on the desired level of detail and output of the models, this involves manipulation of software application source code (programming) and/or linking database fields and objects between various datasets. Many of the 4D CAD commercial applications available contain tools that act as a data bridge between the 3D CAD model and the construction schedule. Not only are skills and knowledge of design and construction required to link the datasets, so is experience with programming objects and database schemas. The main point is that currently

TABLE 28
4D CAD TECHNOLOGY APPLICATION USE BY PROJECT PARTICIPANT

Application	Agency	Consultant	Contractor	N/A
	Reported Percentages/Respondent Count			
Material fabrication	33% (3)	22% (2)	22% (2)	67% (6)
As-built documentation	25% (2)	25% (2)	13% (1)	75% (6)
Constructability review	38% (3)	13% (1)	0% (0)	63% (5)
Communication of methods/systems	0% (0)	0% (0)	0% (0)	100% (7)
Quantity tracking	14% (1)	0% (0)	14% (1)	86% (6)
Public relations	50% (4)	0% (0)	0% (0)	50% (4)
Other	0% (0)	0% (0)	0% (0)	100% (6)

Note: The percentage indicates total respondent ratio; the number represents actual number of respondents selecting the option. N/A = not available.

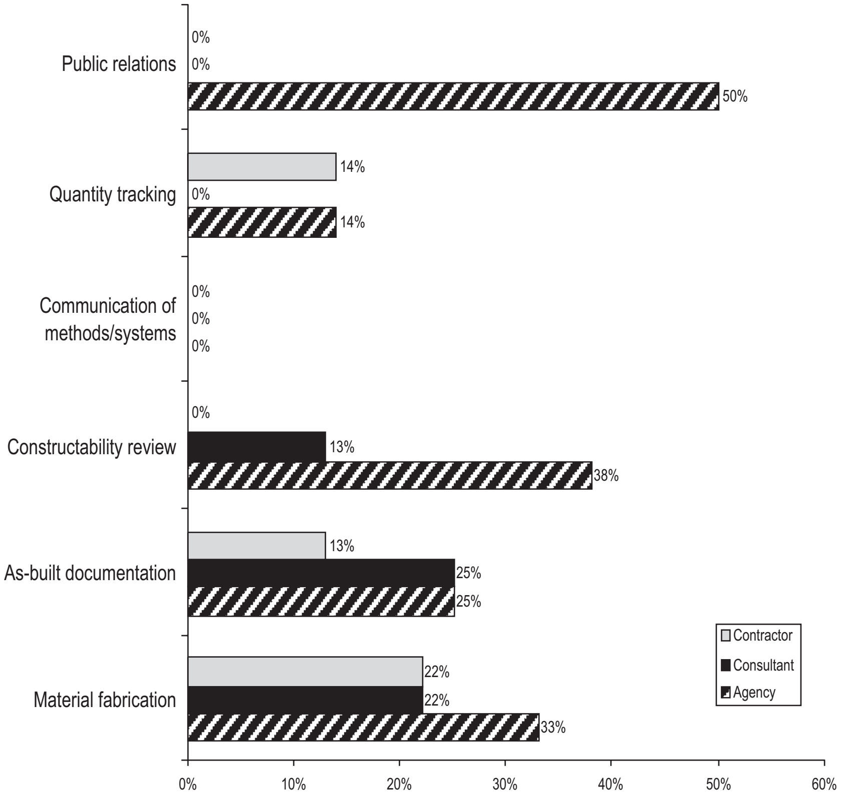


FIGURE 36 4D CAD technology application use by project participant.

off-the-shelf software is incapable of linking the datasets of various software applications that constitute the 4D model.

> Not all 3D models have sufficient attribute information to facilitate automatic linking, so the user has to identify which activity in the project scheduling software program is the activity that drives the component in the model (Smith 2001).

Contract Specification Issues

In CAD software applications the use of multiple drawing layers that overlap foundational design concepts is determined by the user's preference. Standardization of this practice would aid in the development of 3D and 4D models because producers would know where to look for specific datasets.

TABLE 29
USE OF 4D CAD BY CONTRACT TYPE

	No. of Responses	Response Ratio
Design–build	3	38%
Other*	3	38%
Both design–build and design–bid–build	2	25%
Design–bid–build	1	13%
Projects over a certain contract size	1	13%

*Other responses:
1. Not used.
2. Megaprojects > $70 million.
3. Demonstration only.

Agency Procedural Issues

The integration of 4D (and 3D) modeling disrupts the traditional project life-cycle delivery system common to public contracting practices. Although design–build contract procurement is not new to public agencies, the creation of multi-dimensional building models requires the project stakeholders to collaborate much sooner in the early stages of the design process than is otherwise required traditionally. Without this early collaboration, many of the benefits of modeling are lost. Users may need to create new methods of project procurement and contracting, or the contractor could be paid in a separate contract for early collaboration and constructability review. The sharing of project information between the project stakeholders early in the design process is critical.

End-User Technical Skill and Training

Not only do designers need design and construction engineering knowledge and skills to build a successful model, they may also need to have scheduling expertise and considerable computer science, database, and programming skills. The indirect costs of this skill and knowledge must be factored into the total return on investment.

Benefit Awareness

The benefits of 4D CAD are being revealed to those in the construction industry who have not yet experienced it. Periodicals are showcasing the benefits from successful cases on large and high-profile building projects. Additional mechanisms are needed, similar to this report, for disclosing to the industry the benefits of digital modeling to the entire project life cycle. One of the biggest hurdles appears to be quantification of the costs and the uncertainty to owners of the potential payoff (Gao et al. 2005).

Non-Cooperation of Designers

Digital modeling puts more responsibility and accountability on the design engineers. Their early contributions to the project are the foundation on which all other data hinge (as has always been); however, now the design information is used instantaneously, in real time. In this case, the contractor is not reengineering the designer's work to complete his/her, but both disciplines collaborate in creation of the model. This will require a transparency (on both sides) that is not the norm. 4D CAD will require that designers think ahead as to how others will use their data and that they design in 3D. All of the project stakeholders will have to consider the other's perspective.

One mistake commonly made by designers is to take the 3D design to construction and say "Here, use it." However, the construction crew cannot use it because it represents the design version of the project. "The construction guy thinks differently than the designer." The whole database must be converted to a format construction people can use, which has never been done, according to Burger (as quoted in Smith 2001). "The facility design needs to be converted into the construction configuration in which it's going to be built, not the way it's been designed. Once you do that, in 3D or a database model in such a way that the construction guy can deal with it, it becomes much more appealing" (Smith 2001).

The availability of 3D design data has been a stumbling block, says Martin Fischer, director of Stanford University's Center for Integrated Facilities Engineering and a long-time 4D researcher. Much of today's 3D CAD data is based on simple CAD entities and not on still-evolving industry-standard object definitions, he says. Also, he notes that owners are often unwilling to pay for true 3D design and liability-conscious designers are often unwilling to share data (Roe 2002).

Lack of Technology Standards and References

A significant barrier to digital modeling is the lack of standards that can link the datasets of the project stakeholders together. Digital integration requires the ability to link design components to construction components effectively and efficiently. Users are beginning to define common schemas for data classification or Industrial Foundation Classes for the vertical construction industry. Without this standardization for transportation construction, the effort (and cost) of digital modeling will remain high(er).

> Research has shown that the use of data exchange standards, such as Industrial Foundation Classes (IFCs), have, to a certain extent, improved information modeling and exchange between various applications in 4D planning. However, most of this research is still at its infancy. As a result, manual data input still prevails in the industry (Heesom and Mahdjoubi 2004).

> [A]lthough some research initiatives have attempted to introduce a certain level of automation in data exchange, most applications still require some manual input between CAD and databases or databases and schedule information. This labour intensive activity could be considered as a potential reason for the slow uptake of 4D simulations by the construction industry. It was proposed by Kim and Gibson (2003) that one of the main reasons for the low take up of new prototype computer systems in the construction industry was due to their complexity. Therefore, in order to facilitate more widespread diffusion of 4D simulations in the construction industry, 4D systems should be easy to use and require a minimum level of input, allowing the planner to understand and quickly use the tools with a minimal lead in time (Heesom and Mahdjoubi 2004).

Table 30 presents the responses of agencies using 4D CAD of factors that restrict implementation. The sample group is so small that single responses designate the rankings of the factors. Topping the list is agency procedural issues, followed by a tie of end-user technical skill/training and unawareness of the potential benefits. All of the categories received votes, including software interoperability issues, contract specification issues, conflicting technology standards, agency budgeting, hardware availability, and non-cooperation of designers.

TABLE 30
FACTORS RESTRICTING IMPLEMENTATION OF 4D CAD

Factor	No. of Responses	Response Ratio
Agency procedural issues	4	57%
End-user technical skill/training	3	43%
Unawareness of benefits	3	43%
Software interoperability issues	2	29%
Contract specification issues	2	29%
Conflicting technology standards	2	29%
Other*	2	29%
Cost (agency budgeting)	1	14%
Hardware availability	1	14%
Non-cooperation of designers	1	14%

*Other responses:
1. Only for public awareness.
2. Requires signal traffic information and development.

Strategies to Overcome Barriers

- *Document and advertise 4D CAD benefits*: Document time and cost issues, as well as publicly share the experiences within the transportation industry. Develop a knowledge base of multiple case studies similar to what Gao and colleagues (2005) did for building projects.
- *Change design development procedures*: Encourage designers to create 3D models.
- *Change project procurement procedures*: Develop procedures that enable the early collaboration in the creation of digital project models (within or around existing statutory requirements).
- *Develop 4D CAD specifications*: Develop a methodology for designing in 3D and subsequent 4D.
- *Develop model object libraries*: Develop a set of Industrial Foundation Classes for transportation construction.
- *Make agency training available to stakeholders outside*: Open any training delivered to agency personnel in respect to digital modeling to the contractor community.

MODEL FOR SUCCESSFUL IMPLEMENTATION

Table 31 reflects the responses of agencies in ranking factors that have contributed to successful implementation of 4D CAD modeling.

In the vertical construction industry, practices that have contributed to successful project implementations include (as reported in the *Engineering News-Record*) the Denver Art Museum project, which was a publicly funded project:

- Early up-front stakeholder collaboration and maintenance of that collaboration with disciplined periodic team meetings.
- Owner requirements of 3D digital models from the designer as a contractual requirement.
- Detailed and specific contract language concerning iterations of data "hand-off" between the involved project stakeholders.
- Education of field personnel regarding aspects of the system.
- Design model sharing between the parties required intellectual property and implied warranty rights be altered or suspended (Post 2006a,b).
- A successful General Motors project that used digital models; any approved savings or schedule efficiencies were shared among the stakeholders (Sawyer 2005).

BARRIERS TO OVERCOME

The following are both technical and commercial barriers (Wood and Alvarez 2005).

Technical Issues

- Designers must create new models for each project in the transportation industry because the terrain or site model is typically a large percentage of the 3D model.
- Designers must create new models for differing levels of required model detail.
- Access to sophisticated modeling tools requires licensing.
- There is a high cost associated with providing collaborative environments.
- Analysis methods are not yet fully integrated into the simulation.
- The challenges of accommodating differing design, work process, and other database schemas by the project stakeholder involved.

TABLE 31
FACTORS CONTRIBUTING TO SUCCESSFUL IMPLEMENTATION OF 4D CAD

Factor	1 High	2 Medium	3 Low	N/A
Cooperation/support of software application vendors	14% (1)	29% (2)	14% (1)	43% (3)
Comprehensive implementation plan	0% (0)	29% (2)	29% (2)	43% (3)
End-use training	14% (1)	14% (1)	29% (2)	43% (3)
Knowledge of expected benefits	14% (1)	29% (2)	14% (1)	43% (3)
Ease of use	0% (0)	29% (2)	29% (2)	43% (3)
In-house technical support	14% (1)	29% (2)	14% (1)	43% (3)
Cooperation of designers	0% (0)	57% (4)	0% (0)	43% (3)

Note: The percentage indicates total respondent ratio; the number represents actual number of respondents selecting the option. N/A = not available.

Commercial Issues

- The difficulties in determining equitable methods to distribute modeling costs to project participants and beneficiaries (Wood and Alvarez 2005).
- The challenges of getting multiple project stakeholder buy-in (Wood and Alvarez 2005).

UNEXPECTED OUTCOMES

From reported case studies in the literature search, we discovered the following unintended consequences formed as a result of 4D CAD modeling implementation:

- The process forces early collaboration and time expenditures by parties to the contract (Wood and Alvarez 2005).
- Designers are unaccustomed to scrutiny of early design decisions and fear mistake exposures (Wood and Alvarez 2005).
- Decision is strategic regarding level of model detail. If the project embarks on the wrong detail level, bad consequences can occur. Software products are needed that allow the evolution of detail to change as the project progresses.
- In a survey of architects being released this week, 74% of respondents said they use some form of 3D modeling/BIM (Post 2006a,b). The survey does not indicate how many are sharing 3D models with constructors. Many maintain that if they give a BIM to the contractor, they must make design decisions earlier in the process. That could be an issue.
- Contractors and designers experienced in such projects report that the second iteration through the process is much more efficient, suggesting that the initial project will have unforeseen associated incidental costs. This suggests the need for a pertinent knowledge base.
- Legal determination of which party (if any) controls the model—power issues (Hohner 2006).
- A market is developing of consultants with the expertise to develop the 3D and 4D models (from traditional 2D design documents).
- New project development delivery processes will change functional roles; that is, estimators may become planners (Post 2006*a,b*).
- Incorporation of subcontractors (sometimes less technically knowledgeable) into the model team.

CHAPTER SIX

WEB-BASED VIDEO PROJECT MONITORING

DESCRIPTION OF TECHNOLOGY

The use of video cameras on construction sites for display on project and organizational websites has become prevalent in the last ten years. Video cameras that can be remotely controlled through an Internet connection (webcams) have become more sophisticated during this period, and their practical applications have increased. These webcams are used to capture still images on demand, take a series of images at specified time intervals, and capture moving video of construction site activities. The webcam hardware is growing in sophistication and utility with the addition of robotic features and improved image resolution capability. A series of such devices placed on a project site is referred to as a networked robotic camera system. Cameras are feature differentiated by their intended use either inside or outside a construction project facility.

Data Transfer

Data are transferred from the webcam to the Internet through a phone line, broadband Internet, wireless Internet, or phone connection. Once the image data are routed to an Internet protocol address, the images typically are collected in a database hosted on a server. Image resolutions captured by the webcam vary depending on the device. Three and six megapixel digital image cameras are available currently that offer image resolutions of 2048 × 1536 pixels and 2816 × 2112 pixels, respectively.

Output

Users can capture still photographic images of varying display resolutions from webcams, as well as gather streaming video or streaming media. Streaming video is a sequence of 30 or more still images captured per second. As the frame rate (photographs per second) increases, the quality of the streaming video improves (Corley et al. 2005). Streaming video requires high bandwidth to deliver across networks (in compressed form) and especially large storage capacity. For these reasons, streaming video is not a standard option currently provided by webcam manufacturers and service providers. Instead, time-lapse movies can be created from time-lapse images (images captured of a project's work progress taken at periodic time intervals) and specialized software applications.

Installation

Users can either install cameras themselves or hire a service company that can assist in web camera project setup, hardware sales, and web hosting. After users define project goals, they can then determine the number and location of the cameras and install them. Camera configuration and calibration requirements depend on available lines of sight and outcome requirements.

Maintenance

Upkeep of camera hardware is minimal when provided with constant power sources. Some ruggedized outdoor cameras have mechanisms imbedded that minimize condensation development inside the hardware. Users can perform maintenance of the network connection and image capture software and database or outsource these jobs to vendors and service providers.

Hardware Requirements

The main hardware components of a webcam system include the following:

- Camera (can include wide-angle lens, temperature-control sensor, surge suppressor, timer, power converter, heater, and fan);
- Mounting hardware;
- Computer controller;
- Data transmission equipment; and
- Power supply.

Figure 37 shows a cross section of an outdoor web camera's components.

Software Requirements

Software requirements primarily involve the applications that archive the cameras stored images. This is provided as paid service from some of the camera hardware vendors. On projects of long duration, users can capture a significant number of images. The issue of specialized software capable of archiving and retrieving the images when needed, compounded in number by multiple cameras on some jobsites, is a primary consideration.

Figure 38 displays a software application screen view that records daily work progress with associated project images

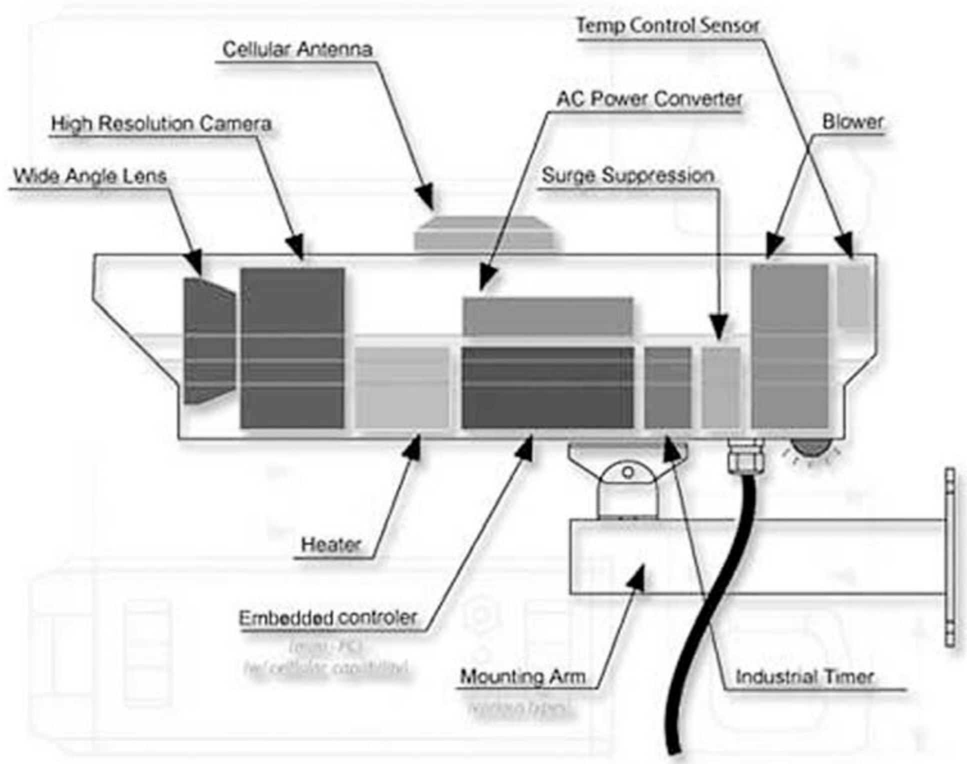


FIGURE 37 Outdoor web camera components (*Courtesy*: OxBlue Corp.).

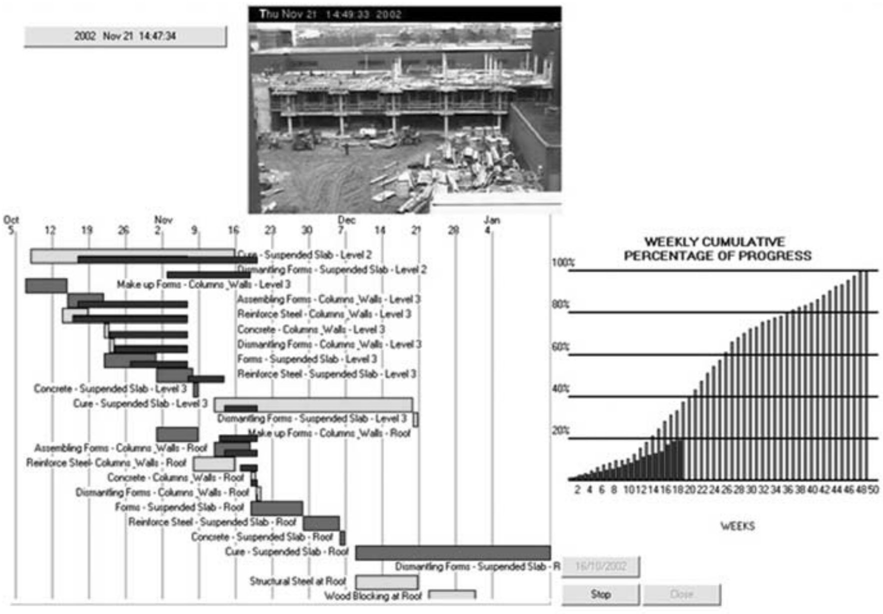


FIGURE 38 Project work progress associated with web camera image (*Courtesy*: Remontech).

captured from a project mounted camera. Figures 39 and 40 display website screen view images from Washington State DOT projects. Figure 41 shows the use of web-based video technology by type and participant.

BENEFITS OF TECHNOLOGY

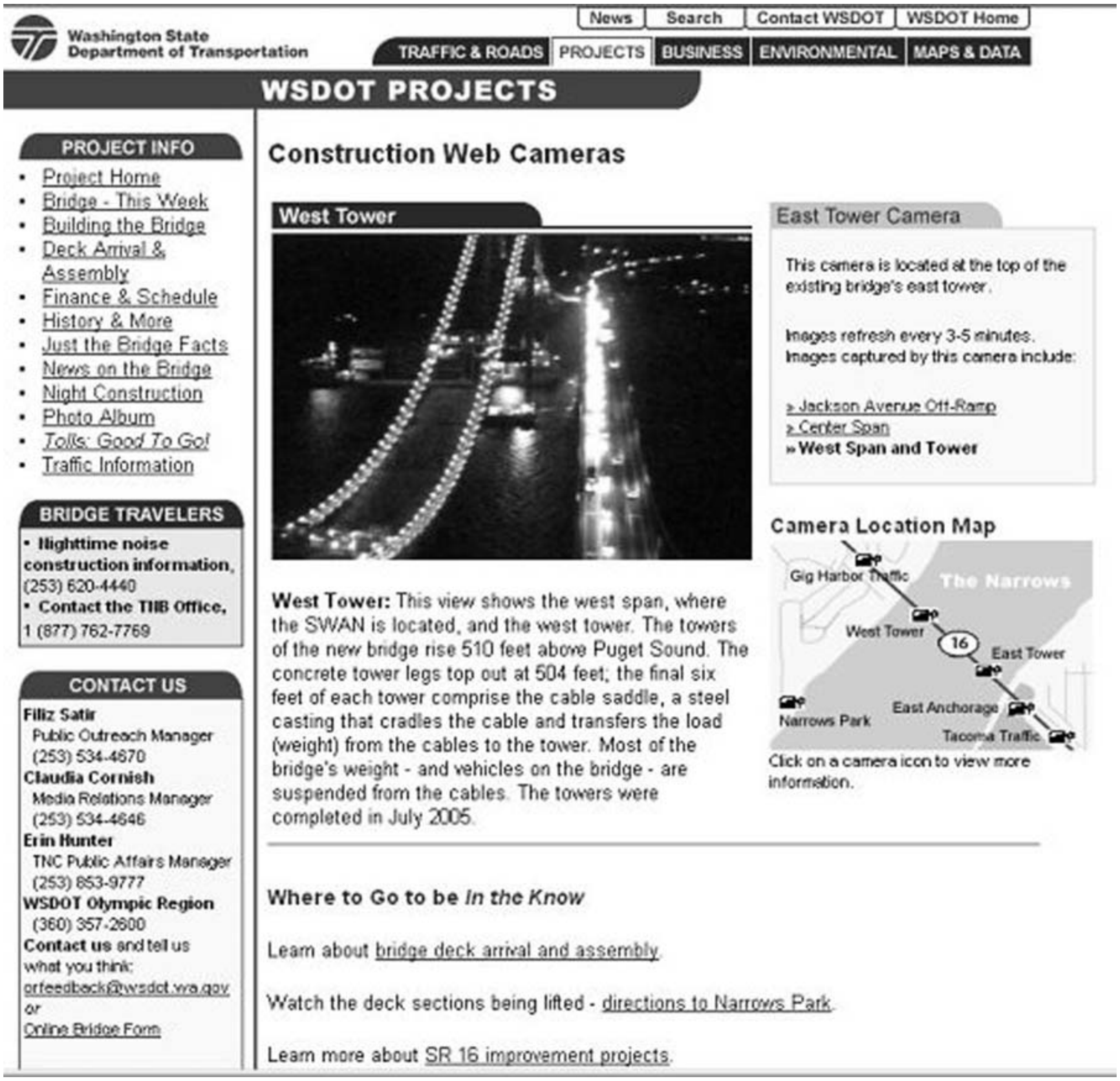
Jobsites with web cameras installed can benefit from the following applications (see Table 32):

- Tracking of jobsite resource use.
- Tracking and documenting of construction work progress.
- Facilitating application with 4D models (as-built sequencing).
- Applying cost accounting.
- Creating historical databases of production information.
- Collecting computer vision-inferring information from images.
- Gathering visual confirmation of jobsite conditions.
- Acquiring image documentation of as-built work schedule and confirmation of contract compliance.
- Validating jobsite activity against other reporting mechanisms.
- Monitoring subcontractor and material procurement activities.
- Monitoring and documenting weather conditions.
- Tracking and monitoring safety compliance.

EXTENT OF USE

Tables 33 through 36 reveal the extent of respondent agency use of web-based video camera monitoring of construction projects. Of 47 responses, 64% are not using the technology, whereas 36% have used it on ten or fewer projects.

Of the respondents who have used web-based video camera technology, more than 72% provide the service as a



Construction Web Cameras

- **Nighttime noise construction information,** (253) 620-4440
- **Contact the TNB Office,** 1 (877) 762-7769

Filiz Satir
Public Outreach Manager
(253) 534-4670
Claudia Cornish
Media Relations Manager
(253) 534-4646
Erin Hunter
TNC Public Affairs Manager
(253) 853-9777
WSDOT Olympic Region
(360) 357-2600
Contact us and tell us what you think:
orfeedback@wsdot.wa.gov
or
Online Bridge Form

This camera is located at the top of the existing bridge's east tower.

Images refresh every 3-5 minutes. Images captured by this camera include:

West Tower: This view shows the west span, where the SWAN is located, and the west tower. The towers of the new bridge rise 510 feet above Puget Sound. The concrete tower legs top out at 504 feet; the final six feet of each tower comprise the cable saddle, a steel casting that cradles the cable and transfers the load (weight) from the cables to the tower. Most of the bridge's weight - and vehicles on the bridge - are suspended from the cables. The towers were completed in July 2005.

Click on a camera icon to view more information.

Where to Go to be *In the Know*

Learn about bridge deck arrival and assembly.

Watch the deck sections being lifted - directions to Narrows Park.

Learn more about SR 16 improvement projects.

FIGURE 39 Washington State DOT website project image from web camera.

Route 15/Gang Mills Interchange (Looking North)

Detailed Photo-Simulations

A photo-simulation is a computer-generated illustration of either the future condition at a particular location or the future appearance of a proposed alternative.

These five photo-simulation galleries compare existing conditions with future improvements at several sites; they are part of the project's Visual Impact Assessment.

FIGURE 40 Washington State DOT website images and simulations.

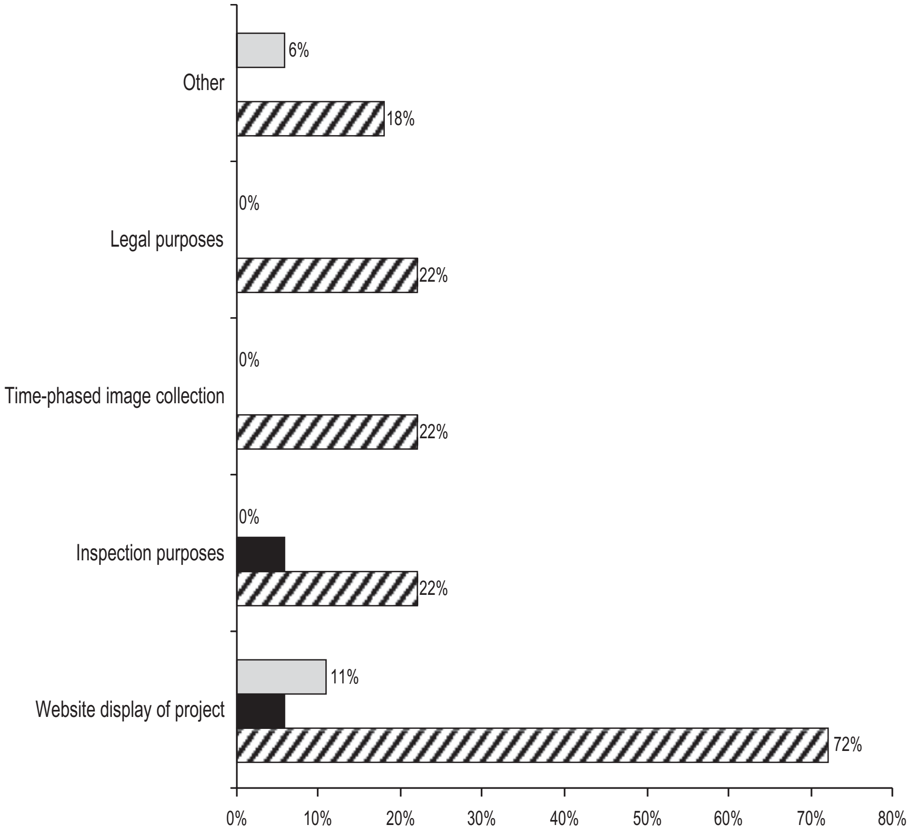


FIGURE 41 Web-based video camera technology application use by project construction type and participant.

TABLE 32
BROAD BENEFITS OF WEB-BASED VIDEO PROJECT MONITORING USE

Application	Process Improvement	Resource(s) Saved
Tracking of jobsite resource usage	Logistical, instantaneous vs. paper documentation	Project administration time, organization of data
Tracking and documenting of construction work progress	Logistical, instantaneous vs. paper documentation	Project administration time, organization of data
Facilitating application with 4D models (as-built sequencing)	Logistical, instantaneous vs. paper documentation	Data/information cycle time, project administration time, organization of data
Acquiring image documentation of as-built work schedule/confirmation of contract compliance	Indemnification or proof of breach of contract	Data/information cycle time, project administration time, organization of data
Validation of jobsite activity against other reporting mechanisms	Indemnification/proof of claim	Data/information cycle time, project administration time, organization of data
Monitoring subcontractor and material procurement activities	Indemnification/proof of claim	Data/information cycle time, project administration time, organization of data
Monitoring and documenting weather conditions	Indemnification/proof of claim	Data/information cycle time, project administration time, organization of data
Tracking and monitoring safety compliance	Indemnification/proof of claim	Data/information cycle time, project administration time, organization of data

benefit to the public as a display on agency websites. Only five agencies reported the collection of images for time-lapse replay. Nine agencies reported collection of images for legal and inspection purposes, whereas two agencies use the technology for traffic monitoring.

REPORTED BARRIERS TO IMPLEMENTATION

Agency personnel report budget issues and benefit unawareness as the leading factors that restrict the use of the technology in their agencies, as shown in Table 37. Table 38 shows that a lack of written specifications does not hinder agency implementation.

TABLE 33
AGENCY WEB-BASED VIDEO CAMERA UTILIZATION, 2005

Project Count	No. of Responses	Response Ratio
None	30	64%
All projects	0	0%
10 or less	15	32%
Most projects when appropriate	0	0%
Other*	2	4%

*Other responses:
1. "1."
2. One project—Joint venture with University of New Hampshire.

MODEL FOR SUCCESSFUL IMPLEMENTATION

Agencies that have successfully employed the web-based camera technology report that, in their opinion, support from hardware and software vendors and suppliers is the most important factor contributing to that success. The responses are shown in Table 39.

TABLE 34
AGENCY WEB-BASED VIDEO CAMERA APPLICATIONS

Application	No. of Responses	Response Ratio
Website display of project	13	72%
Time-phased image collection	5	28%
Legal purposes	5	28%
Other*	5	28%
Inspection purposes	4	22%

*Other responses:
1. Monitoring of traffic in work zones.
2. Have not yet employed, it is under consideration.
3. Traffic monitoring.
4. None.
5. Public information.

TABLE 35
WEB-BASED VIDEO CAMERA TECHNOLOGY APPLICATION USE BY PROJECT CONSTRUCTION TYPE AND PARTICIPANT

Application	Agency	Consultant	Contractor	N/A
	Reported Percentage/Response Count			
Website display of project	72% (13)	6% (1)	11% (2)	22% (4)
Inspection purposes	22% (4)	6% (1)	0% (0)	78% (14)
Time-phased image collection	22% (4)	0% (0)	0% (0)	78% (14)
Legal purposes	22% (4)	0% (0)	0% (0)	78% (14)
Other	18% (3)	0% (0)	6% (1)	76% (13)

Note: The percentage indicates total respondent ratio; the number represents actual number of respondents selecting the option. N/A = not available.

For successful implementation of web-based video project monitoring systems, the following resources and conditions are required:

- Personnel knowledgeable in equipment and system set-up and design.
- Proper equipment specialized to task (e.g., time-lapsed images, streaming video, and as-built documentation).
- Plan, procedure, and/or service provider for storing and retrieving large amounts of digital images or video.
- The ability by means of software application to accomplish desired tasks such as web display, time-lapsed schedule display, and as-built documentation.
- Power supply and availability.

BARRIERS TO OVERCOME

The literature obtained for this report reveals that the major obstacles or barriers to implementation, besides the lack of resources and conditions outlined in the previous section are:

- Lack of understanding/knowledge of the potential applications of jobsite images and video.
- Inadequate financial resources to institute such systems.

UNEXPECTED OUTCOMES

The most obvious predicted outcome of the result in the increased use of web-based video project monitoring might be its effect on the legal climate surrounding project delivery. The presence of the ordered retrieval of indexed job images will heavily affect construction claim and change order dispute resolutions. Construction work progress (production) and resources documented as present on the project at various points in time can more easily be proven with images than with paper documentation.

TABLE 36
USE OF WEB-BASED VIDEO CAMERA BY CONSTRUCTION TYPE

Construction Type	No. of Responses	Response Ratio
Bridge	9	53%
Other*	8	47%
Structure	3	18%
Mass grading	2	12%
All project types indiscriminately	2	12%
Paving	0	0%
Utility location/relocation	0	0%

*Other responses:
1. Large Interstate replacement with extensive Maintenance of Traffic.
2. High-volume urban construction projects.
3. Major interchange work.
4. Major construction.
5. Usually megaprojects, urban projects.
6. None.
7. Major and/or high-impact projects.
8. Some significant paving as needed.

TABLE 37
FACTORS RESTRICTING AGENCY IMPLEMENTATION OF WEB-BASED VIDEO CAMERAS

Factor	No. of Responses	Response Ratio
Cost/agency budgeting	10	56%
Unawareness of benefits	8	44%
Conflicting technology standards	3	17%
Agency procedural issues	2	11%
Network/hardware maintenance	2	11%
Other*	2	11%
Hardware durability	1	6%
End-user technical skill/training	1	6%
Software interoperability issues	0	0%
Slow data transfer/download	0	0%

*Other responses:
1. None, webcams are a cheap novelty.
2. None.

TABLE 38
AGENCY SPECIFICATION STATUS REGARDING WEB-BASED VIDEO CAMERA USE

Written Specification?	No. of Responses	Response Ratio
Yes	1	5%
No	18	95%

TABLE 39
FACTORS CONTRIBUTING TO SUCCESSFUL AGENCY IMPLEMENTATION OF WEB-BASED VIDEO CAMERA USE

Factor	1 High	2 Medium	3 Low	N/A
Support of hardware vendor/supplier	11% (2)	56% (10)	6% (1)	28% (5)
Support of software vendor/supplier	6% (1)	61% (11)	6% (1)	28% (5)
End-user training	0% (0)	59% (10)	18% (3)	24% (4)
Knowledge of expected benefits	11% (2)	61% (11)	11% (2)	17% (3)
Ease of use	28% (5)	28% (5)	22% (4)	22% (4)
In-house technical support	11% (2)	17% (3)	50% (9)	22% (4)
Comprehensive implementation plan	0% (0)	28% (5)	50% (9)	22% (4)
Other-1	8% (1)	0% (0)	0% (0)	92% (12)
Other-2	8% (1)	0% (0)	0% (0)	92% (11)

Note: The percentage indicates total respondent ratio; the number represents actual number of respondents selecting the option. N/A = not available.
Other-1 responses:
1. Traffic monitoring.
Other-2 responses:
1. Public information.

CHAPTER SEVEN

OTHER TECHNOLOGIES USED FOR CONSTRUCTION DELIVERY

VIRTUAL REALITY

VR holds substantial potential benefits for the transportation industry. Highway construction projects are directly related to traffic flows and the user experience of traveling the eventually completed project. VR enables designers and planners to "sit in the driver's seat" of a virtual project and experience variables of the design such as traffic flow, driver line of sight, signalization and signage placement, maintenance of traffic, and other driver experiences. When VR applications are used in conjunction with digital models, designers and planners can experience the results of their decisions virtually, before construction begins and final decisions are made. Although the visualization benefits of this technology in the building construction segment is certainly also available for transportation projects, the variables involved in experiencing facility usage virtually is a benefit unique to the transportation industry.

BUILDING INFORMATION MODELS

Digital modeling in the vertical construction industry is called BIM. Efforts are underway to define and standardize the process.

> The National Institute of Building Standards is creating a National BIM Standard (NBIMS), set for publication by year-end [2007]. The federal General Services Administration is publishing the first part of a guideline for 3D and 4D (the dimension of time) BIM, due out in August. The American Society of Civil Engineers and the American Council of Engineering Cos. are holding BIM workshops and BIM strategy sessions for structural engineers. The first is June 22, in Chicago. People have yet to agree on fundamentals, such as a BIM definition. A definition is important because "many architects feel they cannot begin to use building modeling until there are entirely new delivery methods, contract relationships and insurance mechanisms in place," says E. Davis Chauviere, chief information officer for architect–engineer HKS Inc., Dallas.
>
> Few would argue that BIM is a potentially great tool for planning, design, analysis, system coordination, fabrication, construction, and facilities management. BIM-based project delivery, even in an immature stage, is "much more intelligent" than the traditional, 2D process based on plans, sections, and elevations, says Jeff Millett, director of information and communications technologies with Stubbins Associates Inc., a Cambridge, Mass.-based architect.
>
> Some say there will eventually be a single BIM, managed by the architect or the constructor. Others see multiple design models integrated into one by the architect and multiple construction models, integrated into one by the constructor. Each entity will have a model keeper to coordinate design and construction models.
>
> BIM works best in a collaborative rather than adversarial atmosphere. Jim Jonassen, managing partner of architect NBBJ, Seattle, envisions a process in which design and construction phases overlap, with appropriate team members taking the lead in different phases, with participation by other players (Post 2006a,b).

RADIO FREQUENCY IDENTIFICATION

RFID is a technology that is currently growing in use in other industries such as manufacturing and retail. It is likely that most people have purchased goods at a retail outlet in which the product had RFID tags attached for supply chain management, inventory, and/or prevention of theft. Small chips or "tags" with the ability to send data signals through radio waves are attached to physical objects. These tags are also referred to as transponders. The data signals are received by an "interrogator" or "reader" for interpretation of the tag's data. Readers can be stationary or mobile (HHC). Innovation with this technology is proceeding rapidly. Tags are now available that have sensor capabilities and that can both send and receive signals. This technology will most likely replace many bar code scanning operations. The construction industry has begun to realize the efficiency potential of this technology, and FIATECH has conducted several research and development case studies to prove and advance the cause. The transportation industry has embraced RFID technology through uses such as railcar management, fleet management, toll fare collection, equipment identification, and fuel dispensing (Schneider 2003). Construction RFID documented applications from the literature search include materials management and small tools management. Applications are plentiful, especially in relation to automatic temperature and maturity tracking of portland cement and asphalt concrete. The five technologies that are the basis of this report each have potential applications involving RFID technology. The Michigan DOT conducted a successful pilot test using RFID for concrete maturity in 2003 (DeFinis 2005). Chin et al. (2005), in partnership with the Samsung and DoallTech Corporations, have experimented with a combination 4D CAD + RFID system for tracking project progress.

GROUND PENETRATING RADAR

Also referred to as ground probing radar, georadar, subsurface radar, and earth sounding radar, GPR is a subsurface mapping technology that is non-destructive in its application. The technology can be used to locate underground utilities, unexploded land mines, groundwater, caves, tunnels, archeological sites, and other unseen objects without requiring excavation or destruction. Users can engage GPR from ground surface, boreholes, aircraft, and satellites with resolutions equal to or greater than existing radar. Hardware includes a radio transmitter and receiver attached to ground-mounted antennae. The radio waves penetrate the ground and detect differing electrical properties in earth strata, which then form an image on a display device. Effective penetration depths vary from 3 to 1,600 ft depending on strata density and material properties (Wood and Alvarez 2005).

ELECTROMAGNETIC SENSORS

Electromagnetic sensing can be use in combination with GPS systems to determine physical properties of a ground area such as moisture or volume. The agricultural industry has used this technology for some time. The technology used microwaves to detect differences in subsurface properties. Current applications include mapping of underground storage tanks, landfill and trench boundaries, and detection of contaminants and buried ordinance (Haas et al 2000).

LASER DETECTION AND RANGING

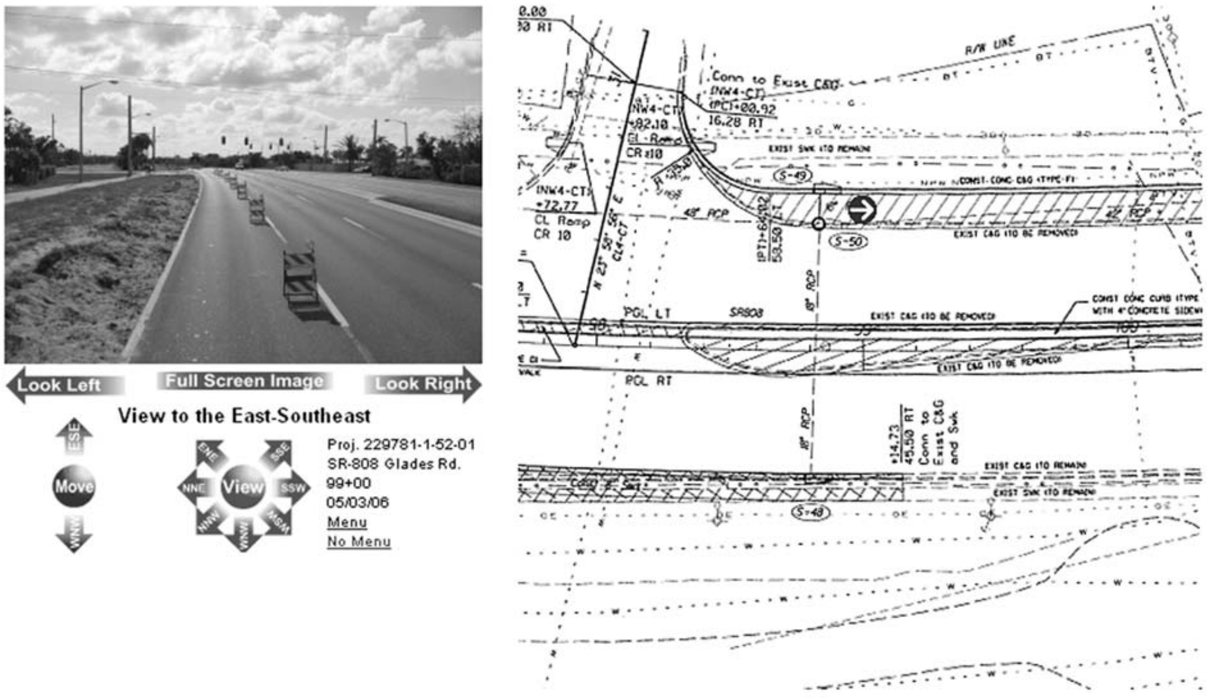
LADAR—Laser Radar—is described as a

> . . . device consisting of a photon source (frequently, but not necessarily a laser), a photon detection system, a timing circuit, and optics for both the source and receiver. Distance from the device to targets struck by the emitted photons is measured by the time-of-flight (TOF) divided by the speed of light. Strictly speaking the device could be a single shot "0-D" measurement system (range only), but these are more commonly referred to as laser rangefinders. LADAR, on the other hand, is generally assumed to generate a 3-D Range Image (Stone et al. 2004).

LADAR systems can conduct rapid 3D imaging of construction sites. Applications include tracking project work progress, location of critical materials or equipment, and monitoring for defects and variations. Slattery and Kharbanda (2006) describe the technology as a "device which generates a three-dimensional surface point map of the current state of any site." Their research combines the use of web cameras with LADAR to monitor steel erection on a construction site; they term the combination of systems "computer vision" (Slattery and Kharbanda 2006).

VIRTUAL AS-BUILTS

The Florida DOT has contracted with an outside consultant to document the work progress on their projects. The technology consists of mounting a series of cameras with wide-angle lenses on a mobile unit (truck or van). The vehicle rides the project at periodic intervals (every two weeks) and captures images in a 360 degree radius. These images are linked to "points of view" on the contract plan drawings and made available on a website. When viewing the website, users can observe job conditions (images) as if they were standing at the point of view by clicking on directional arrows on the page. Figure 42 displays a page of the website and the navigational controls for panning the view (www.visualasbuilts.com/SR80801/).



View to the East-Southeast

Proj. 229781-1-52-01
SR-808 Glades Rd.
99+00
05/03/06

FIGURE 42 Virtual as-built web page (*Courtesy*: Visual As-Builts).

CHAPTER EIGHT

ANTICIPATED DEVELOPMENTS

Digital technologies are encroaching swiftly upon the construction industry. We are beyond the time where the technology exists but there is no experienced practical application, because there are now applications of these tools that a decade ago would have sounded extreme. Newspaper, magazine, and academic journals have documented successful implementations of the technologies described in this report. In 2005, the transportation industry sponsored a team-led study of the use of these technologies adopted by the private commercial building industry. One of the implications of the study's findings, and certainly a conclusion formed from the literature search for this study, is that 3D (and other multi-dimensional) modeling is a process that is here to stay (Friedland 2005). The rate of the industry's adoption may be in question, but the benefits of using this technology are not. Like many new technologies, its proper use requires a shift in the prevailing methods of conducting business.

Multi-dimensional modeling can serve a constructed facility throughout its entire life cycle, from design through decommission. Beginning with the facility's conceptual design, alternate building systems, methods, and materials can be simulated in what-if scenarios with minimal effort or requirement of time. 3D modeling allows users to develop the project virtually before the physical construction begins and resources are extended. By these iterations of simulated building, users can identify and correct mistakes and oversights before they actually occur. At groundbreaking, 3D terrain models and GIS mapping can assist in the design and planning phases. Bidding phases can be shortened because the sharing of digital models eliminates the requirement of quantity take-off (a process of reverse engineering the design drawings). Developers can use this initial 3D digital model for construction purposes through use in project layout and machine-guided grading operations. As developers build the site work, they can append the model with work progress quantities for owner payment purposes and as-built documentation. The technologies studied in this report are tools to add information to these life-cycle models. HHCs, temperature sensors, maturity meters, web cameras, and GPS receivers are specific tools now available that can input and retrieve data from the project model. By use of these interactive tools, the access and input of model data, especially through wireless networks, is termed the "connected" or "smart" jobsite.

The digital modeling concept is not reserved for terrain and site work. Users can model any facility or its components with the ensuing benefits as has been proven in the vertical construction industry. Application in the transportation realm would encompass earthwork, paving, bridge, and subsurface facilities. The models could be encompassing or separated.

For this process to work efficiently, sharing of the model's data is paramount. All of the project stakeholders require data from the model for differing purposes and at differing times throughout the facility's life. This is where the paradigm shifts are required. Contractors, vendors, subcontractors, utility representatives, and the like require earlier involvement in the design and planning processes. For constructability and simulation purposes, all need access to the model and its data. To owners, the impact will be more cost-efficient projects overall, with increased costs in the earlier phases of the facility life cycle (design and planning). Throughout the life of the facility, users can add information to the model and access information from the model.

Based on what the literature search revealed, it appears that owners will have to drive the process. In all of the case study's collected, it was the owner who mandated and specified that the project delivery method would involve 3D digital modeling. This appears to be an opportunity for the transportation construction industry to take a lead in the development of this project delivery methodology and to save project costs and duration as a result. It would also be a conclusion that use of VR would find more applications in the transportation industry than other construction industry segments. VR tools enable the user to experience the constructed facility as early as the design phase. In an industry that is rightly concerned with the comfort and benefit of the traveling public, the ability to sit in a virtual car and experience the results of the facility's design decisions is fantastic.

For all of these components to merge together, a great deal of knowledge and technology transfer must occur as reflected in this study's survey. In *NCHRP Synthesis of Highway Practice 355*, Harder and Benke (2005) state that:

> Technology transfer is defined as the activity leading to the adoption of a new-to-the-user product or procedure by any user or group of users. New-to-the-user means any improvement over existing technologies or processes and not only a recent invention or research result. Technology transfer includes research results implementation and product or process deployment. Activities leading to the adoption of innovations can include knowledge transfer, training, and education, demonstrations and showcases, communications and marketing efforts, and technical assistance.

> In addition, in this transportation context, technology transfer includes the complex process of change, a comprehensive achievement dealing with cultural as well as technical issues.

Successful technology transfer occurs when the following factors are present:

- There is a push of technology into a user environment.
- There is a champion associated with the research and technology transfer effort.
- Pilots and demonstrations allow hands-on learning.
- Senior management support attracts attention, leads by example, and gives guidance to the effort.
- Early involvement of the user allows early resolution of problems and prepares the user for fully embracing the innovation.
- There is a technology transfer or implementation plan to identify strategies and tactics.
- Qualified people are in lead roles.
- Partnerships leverage resources and attract the right participants.
- There is progress monitoring and committed funding.
- There is a focus area for technology transfer efforts.
- Emphasis is on marketing and communications.
- Benefits of the technology meet users' needs.

In the course of performing this study two categories of actions were noted. Technology transfer agents and their organizations tended to encourage others to adopt or apply innovations that would benefit a potential user; in essence, "pushing" the technology out into the transportation community for it to be used. At other times, organizations or their technology transfer agents sought technologies or innovations to apply to specific problems or, in essence, pulling the technology into the agency for use.

The top three needs of state DOTs were: (1) more time to perform technology transfer, (2) additional funding, and (3) technology transfer training. State DOTs believe they could use training in the processes of technology transfer. Local Technical Assistance Program (LTAP) centers consider technology transfer training as one of their lowest-ranked needs, most likely because the centers see these skills as existing strengths and do not place a priority on further enhancing these skills in place of addressing other more pressing needs.

The LTAP centers consider additional funding as the single most important need. The other needs cited by more than half of the LTAP respondents are greater management support for technology transfer, more trained staff, greater access to technical expertise, and assistance for management and administrative responsibilities associated with technology transfer.

A number of state DOTs and LTAP centers reported needs in the areas of management and administrative processes associated with making others aware of and encouraging others to use innovations. These are listed here in order of the rated need for each state DOT and LTAP/Tribal Technical Assistance Program (TTAP) center:

- State DOTs
  - Implementation plans
  - Evaluation and assessment procedures
  - Executive briefing models.
- LTAP/TTAP centers
  - Evaluation and assessment procedures
  - Executive briefing models
  - Marketing plans.

For state DOTs, additional funding, added time for conducting technology transfer, and greater senior management support are the three most frequently mentioned areas of need when pulling promising technologies into the organization (Harder and Benke 2005).

Additionally, Zimmerman et al. in *NCHRP Synthesis of Highway Practice 296* (2001) stated that:

> State DOTs often face critical skill shortages and staff training needs that are only exacerbated by the proliferation of the new I/C [information and communication] technologies. To benefit from these new I/C technologies, state and local transportation agencies must either retrain existing staff to upgrade their engineering and management skills or hire new staff with the requisite skills. The case studies illustrated that outsourcing, use of consultants, personal computer "seat management," and hiring bonuses are just some of the management tools that state DOTs are using to address staff shortages.

These studies indicate that one of the largest barriers to implementation of these technologies is that of technology transfer, training, and education. In the case of the technologies in this study, the greatest need appears to be advertisement in the benefits of use, followed by education and training in the implementation of the technologies.

Specific implementation and use training is required in the following disciplines:

- 3D design
- 3D data extraction and interoperability with other software applications
- 4D CAD modeling
- Setup of networked jobsites
- GPS surveying and mapping
- GPS stakeless grading
- Use of HHCs and related software applications
- Data exchange with HHCs
- Portland cement concrete maturity method and temperature tracking
- Use of remote project web cameras for contract documentation.

Anticipated future technological developments include tools for monitoring, guiding, and coordinating construction equipment and robots, ultrasonic and optical systems.

Finally, the increased concern over privacy, intellectual property, and security will expand the use of Digital Rights Management in networks and software. Who will "own" legally or in a liability sense the digital model or the data it contains? Will all who need be granted access? If the model contains legal documents will they be authenticated by digital signatures?

CHAPTER NINE

CONCLUSIONS AND FUTURE RESEARCH NEEDS

The information contained in this synthesis isolates five technologies for a brief examination of their characteristics and their current rate of adoption by transportation agencies in the design and construction of facilities. As the originators of this synthesis topic no doubt knew, the study's conclusions would be about more than the individual technologies themselves. Looking broadly at the information contained in this report, the following conclusions can be reached:

- These technologies, along with others, constitute what will be known initially as the "smart jobsite" or "connected jobsite." All of these technologies can be used (eventually) together to more efficiently deliver the life-cycle stages, phases, and tasks of constructed transportation facilities.
- The digital model of constructed facilities will eventually be the data center or single point of containment of information specific to that facility throughout the entire life-cycle process. From design through decommission, the collaborative digital model will contain all the data generated from successive stages of that project's life cycle. No longer will the data be separated in "data-silos" horded by individual facility stakeholders.
- Owners will be the drivers of the digital model delivery method, giving the transportation industry the opportunity to take the lead in the adoption of the technology.
- We are in the formative stages of this transformation. Technologies exist that can assist in the delivery of construction projects, but needed products, properly trained human capital, and institutional configurations are either not sufficiently available or adapted.
- The technologies and their integration will require specialists to configure and interpret results, but not necessarily to administrate or utilize.
- Return on investment data are sorely needed to spur adoption.
- Mechanisms are needed to disseminate knowledge and information about new technologies to managers and strategic planners of transportation agencies, and then to those personnel who directly deliver projects.
- Specialized education and training mechanisms are required for adoption, implementation, and maintenance of the new and changing technological applications and products.
- The information contained herein is merely a "snapshot" of the current state of practice affairs that will have changed by the time of publication.
- That "champions," early adopters of a technology, in association with agencies, industrial product specialists, and academia can encourage adoption and new application of technology that benefits the entire industry.

The following are areas for further study.

- Documented case studies with emphasis on return-on-investment analysis and implementation costs.
- Case studies and research concerning the balancing of contractual risks and rewards on projects using digital modeling that are specific to the transportation industry.
- Pilot projects.
- Research dedicated to integration of these technologies on the jobsite.
- Wireless communication for Internet connectivity and/or data transmission.
- Global positioning system-collected production information and how to document for as-built diagram or models.
- Prototype of handheld computer specific for construction jobsites, integrating all required technologies and products.
- Contractual incentives for use and experimentation with technology, as well as for distribution of technological risk.
- Study of legal ramifications regarding the use of these technologies and the corresponding adjustments required in construction documents and delivery methods.

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GLOSSARY OF ABBREVIATIONS AND ACRONYMS

2D—Two dimensional; typically pertaining to length and width.

3D CAD—Three-dimensional computer-aided design.

4D CAD—Four-dimensional computer-aided design; the usage of 3D CAD integrated with scheduling (3D + time).

Bandwidth—A measure of frequency range, measured in hertz (Hz), associated with Internet and radio communication (in this report).

BIM—Building information model.

CAD—Computer-aided design.

CORS—Continuously operating reference station.

DEM (digital elevation model)—Topographical designs that communicate existing and design workspaces.

Desktop virtual reality—A non-immersive approach to virtual reality (VR); the VR is displayed on the computer desktop.

DGPS—Differential global positioning system.

Display resolution—Refers to fixed-pixel-array displays such as cathode ray tube and liquid crystal display computer screens and is the measure of the physical number of rows and columns of pixels creating the display.

DTM (digital terrain model)—Same as DEM.

DVR—Distributed virtual reality.

GPS—Global positioning system.

HARN—High accuracy reference network.

Immersive virtual reality—A virtual reality/artificial environment in which the user is as immersed as they usually are in consensus reality.

IVFP (Immersive Virtual Facility Programming)—A prototyping technique that addresses the facility's product and processes as well as the media in which the model is displayed.

Lean construction—A production management-based approach to project delivery (see www.leanconstruction.org).

MBD (Model-based design or integrated building models)—Any design method using 3D models to create and manage realistic and complete electronic simulations of buildings, before their completed construction or during the operations of the facility.

NDGPS—National differential global positioning system.

Pixel (picture element)—The smallest component of an image or picture on a cathode ray tube screen (usually a colored dot).

POP modeling—Product, Organization, and Process.

Prototyping—Creation of a model and the simulation of all aspects of a product.

Real time—Of or relating to computer systems that update information at the same rate as they receive data, enabling them to direct or control a process such as an automatic pilot.

RFID—Radio Frequency IDentification (chips).

RTK—Real-time kinematic surveys.

Real-time kinematic survey transponder—Also known as a "tag," in relation to RFID, and classified as either active or passive.

TIN—Triangulated irregular network.

VDC—Virtual design and construction.

VR—Virtual reality: An environment that is simulated by a computer.

VRS—Virtual reference system.

APPENDIX A

Survey Questionnaire

QUESTIONNAIRE FOR NCHRP SYNTHESIS TOPIC 37-06
TECHNOLOGIES FOR CONSTRUCTION DELIVERY

Thank you for your consideration and time as a responder to this National Cooperative Highway Research Program (NCHRP) Synthesis survey. After reading the Purpose, Background, Definition, and Scope sections below, you may find that specific questions may be better responded to by some other individual(s) in your organization. The synthesis consultant wishes to assist you in any way in order to allow your response. The survey should take between 10 and 20 minutes of your time. We would like to collect your responses in the manner most convenient to you:

1. The survey is available online at: http://www.zoomerang.com/survey.zgi?p=WEB224ZTG88HM5 and is easily taken from a web browser with Internet access. Multiple responders from the same agency are allowed. Each respondent can complete a separate survey or complete separate pages within the same survey.
2. The survey can be taken and e-mailed to the consultant from within this document (by populating the document with answers and clicking on the "Submit by Email" button at the top and bottom of this form. The free Adobe Reader Version 7.0.7 is required for this functionality. The software application can be downloaded from this link: http//www.adobe.com/products/acrobat/readstep2.html.
3. The survey can be printed from this form, populated with answers, and either faxed or sent via U.S. Mail to the consultant.
4. The survey response can be given orally over the telephone to the consultant or his assistant by scheduling a phone meeting.

Please return the completed questionnaire by March 31, 2006 to:

John J. Hannon or Brannon Myrick
NCHRP Synthesis Topic 37-06 Consultant
The University of Southern Mississippi
School of Construction
118 College Drive, #5138
Hattiesburg, MS 39406-0001
E-mail: john.hannon@usm.edu
Phone: 601-266-5550
Fax: 601-266-5717

If you need clarification, or after completing the survey there are issues pertaining to these technologies for construction delivery within your agency that you believe are important, but are not adequately addressed by the survey, please feel free to contact the consultant directly.

PURPOSE

The purpose of this synthesis is to identify the extent of utilization, benefits to implementation, models for successful implementation, and unresolved issues within transportation agencies of five emerging technologies that have the potential to automate the delivery of construction projects.

DEFINITION AND TERMINOLOGY CLARIFICATION

Construction delivery: Please report technologies utilized by your agency only in the construction stage of projects.

GPS (global positioning system): A system of satellites, computers, and receivers that is able to determine the latitude and longitude of a receiver on earth by calculating the time difference for signals from different satellites to reach the receiver.

Handheld computer: A portable battery-powered computer small enough to be carried and used in the field.

Automated temperature tracking: Sensor and processing devices with the ability to measure and record concrete temperature during the curing process in order to predict concrete strength.

4D CAD: A 4D model is developed by linking the critical path construction schedule to a 3D CAD (computer-aided design) model. Virtual reality (VR).

WebCam: A camera designed to take digital photographs and transmit them over the Internet or other network.

SCOPE

This synthesis study will provide information on the use of these technologies by transportation agencies for construction of projects. The technologies to be explored will be: (1) GPS for payout, machine guidance, and quantity tracking; (2) handheld computers for construction records (e.g., inspection, materials testing, and quantity tracking); (3) automated temperature tracking for concrete maturity monitoring to optimize concrete placement for bridge road construction; (4) 4D CAD modeling for constructability analysis and for improved communications (public outreach, visualization of project staging); and (5) remote project monitoring with the web-based video cameras.

The focus of the study is on technologies used directly in the construction of a project. Information to be gathered will include:

1. For each technology:
    a. Description and benefits of the technology (cost/benefit information is available)
    b. Extent of use
    c. Barriers to implementation and strategies to overcome barriers (including case studies)
    d. Model for successful implementation (e.g., contract structure, specifications, phase-in, training, technology infrastructure, management support, local champions, etc.)
    e. Unresolved issues and unintended consequences relating to the use of each technology.
2. Other beneficial technologies identified by the agencies as currently being used for construction delivery.
3. Anticipated developments (such as Flash RADAR and concrete maturity modeling).
4. Future research needs.

NCHRP Synthesis 37-06: Technologies for Construction Delivery

1. Please provide us with your respondent information.

Name: ____
Agency: ____
Address 1: ____
Address 2: ____
City/town: ____
State/province: ____
Zip/postal code: _______________________________________
E-mail address: ____
Phone number: ____

2. What is your job title (functional role)? ________________________________

3. Which best describes the function of your business unit?

Central oversight group: _____________________________________
Resident engineering office: __________________________________
Other, please specify: _______________________________________

4. [Construction Projects Delivered] Approximately how many projects (all types) does your agency deliver annually?
____

GPS

5. In 2005, how many projects utilized GPS technology during construction?

_____ None (If "None," please click "Submit" at bottom of page)
_____ 10 or less
_____ 10–30
_____ 30 or more
_____ Other, please specify number if known: _________

6. Please indicate your level of satisfaction for each of the GPS application(s) utilized in the delivery of construction projects (check all which apply). [Select: High (1), Medium (2), Low (3), N/A.]

Layout	1	2	3	N/A
Staking by agency	1	2	3	N/A
Pay quantity measurement	1	2	3	N/A
Machine guidance	1	2	3	N/A
Utility/drainage location	1	2	3	N/A
Inventory tracking	1	2	3	N/A
Landscape seeding	1	2	3	N/A

7. Please indicate GPS applications utilized in construction project delivery not listed in Question 6, and your level of satisfaction for each.

Other 1: describe application: ____

1 2 3 N/A

Other 2: describe application: ____

1 2 3 N/A

8. Please indicate who of the project stakeholders utilizes GPS technology in layout/staking applications:
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

9. Please indicate who of the project stakeholders utilizes GPS technology in pay quantity measurement applications:
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

10. Please indicate who of the project stakeholders utilizes GPS technology in utility/drainage location applications:
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

11. Please indicate who of the project stakeholders utilizes GPS technology in (Question 7): Other-1 applications:
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

12. Please indicate who of the project stakeholders utilizes GPS technology in (Question 7): Other-2 applications:
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

13. Please indicate the types of construction in which GPS application(s) are most beneficial. (Check all that apply.)
_____ Paving
_____ Bridge
_____ Utility location/relocation
_____ Non-bridge structure
_____ Other, please specify: ____

14. In delivery projects that have utilized GPS technology, what significance have the following factors had in contributing to the success of GPS implementation at you agency. [Select High (1), Medium (2), Low (3), N/A.]

Cooperation of surveyors	1	2	3	N/A
Cooperation of agency designers	1	2	3	N/A
Clear & comprehensive contract specs	1	2	3	N/A
End-user training (agency)	1	2	3	N/A
End-user training (contractor)	1	2	3	N/A
Equipment sharing between agency & contractor	1	2	3	N/A
Hardware/software vendor support	1	2	3	N/A

15. Please indicate any other factors beyond those listed in the previous question that have contributed to the success of GPS implementation at your agency and the level of significance. [Select High (1), Medium (2), Low (3), N/A.]

Other, please specify: ____

16. Which type of base station network(s) is/are utilized by your agency? (Check all which apply.)
_____VRS
_____CORS
_____NDGPS
_____OPUS
_____HARN
_____Do not know
_____Other, please specify: ____

17. In your opinion, which of the following factors are involved in restricting GPS technology usage for construction project delivery in your agency? (Please mark all that apply.)

_____Cost (agency budgeting)
_____Legal issues
_____No contractor payment mechanism
_____Unawareness of benefits (agency)
_____Unawareness of benefits (contractor)
_____Procedural issues (agency)
_____Network maintenance
_____End-user technical skill (agency)
_____End-user technical skill (contractor)
_____Lack of specification by agency
_____Conflicting technology standards
_____Lack of design support
_____Lack of GPS equipment (agency)
_____Lack of GPS equipment (contractor)
_____Other, please specify: ____

18. Which phrase best describes your agency's specifications with respect to GPS?
_____Our agency specifications allow unlimited use of GPS during construction.
_____Our agency specifications allow limited use of GPS during construction.
_____Our agency specifications prohibit GPS use during construction.
_____Our agency specifications mandate GPS use during construction.
_____Our agency specifications are silent on use of GPS during construction.

19. Do you have any cost and/or benefit information on this technology?
_____ Yes _____ No

20. May we follow up with a few clarifying questions?
_____ Yes, prefer e-mail
_____ Yes, prefer phone
_____ No

Handheld PC

21. On approximately how many projects per year has your agency utilized handheld computer technology in the delivery of construction projects?
_____ None (If "None" chosen: click "Submit" at bottom of page).
_____ All projects
_____ 10 or less
_____ Most projects when appropriate
_____ Other, please specify: ____

22. For which purposes are handheld computers utilized in the delivery of construction projects? (Please check all that apply.)
_____ Contract documentation (daily diaries)
_____ Material delivery, tracking, disposition
_____ Voice communication
_____ Internet communication
_____ GPS location/measurement
_____ Bar code scanning
_____ Radio frequency identification (RFID)
_____ Material testing (QA/QC)
_____ Construction workmanship (QA/QC)
_____ Cost tracking
_____ Contract time tracking
_____ Other, please specify: ____________________________________

23. Please indicate who of the project stakeholders utilizes handheld computer technology for contract documentation (daily diary) purposes:
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

24. Please indicate who of the project stakeholders utilizes handheld computer technology for material delivery tracking, disposition purposes:
______ Agency staff
______ Construction management/testing consultants
______ Contractors
______ N/A

25. Please indicate who of the project stakeholders utilizes handheld computer technology for voice communication purposes:
______ Agency staff
______ Construction management/testing consultants
______ Contractors
______ N/A

26. Please indicate who of the project stakeholders utilizes handheld computer technology for Internet communication purposes**:**
______ Agency staff
______ Construction management/testing consultants
______ Contractors
______ N/A

27. Please indicate who of the project stakeholders utilizes handheld computer technology for GPS location/measurement purposes:
______ Agency staff
______ Construction management/testing consultants
______ Contractors
______ N/A

28. Please indicate who of the project stakeholders utilizes handheld computer technology for bar code scanning technology:
______ Agency staff
______ Construction management/testing consultants
______ Contractors
______ N/A

29. Please indicate who of the project stakeholders utilizes handheld computer technology for radio frequency identification purposes:
______ Agency staff
______ Construction management/testing consultants
______ Contractors
______ N/A

30. Please indicate who of the project stakeholders utilizes handheld computer technology for material testing (QA/QC) purposes:
______ Agency staff
______ Construction management/testing consultants
______ Contractors
______ N/A

31. Please indicate who of the project stakeholders utilizes handheld computer technology for construction workmanship (QA/QC) purposes:
______ Agency staff
______ Construction management/testing consultants
______ Contractors
______ N/A

32. Please indicate who of the project stakeholders utilizes handheld computer technology for cost tracking purposes:
______ Agency staff
______ Construction management/testing consultants
______ Contractors
______ N/A

33. Please indicate who of the project stakeholders utilizes handheld computer technology for contract time tracking purposes:
______ Agency staff
______ Construction management/testing consultants
______ Contractors
______ N/A

34. Please indicate who of the project stakeholders utilizes handheld computer technology for other (Question 22) purposes:
______ Agency staff
______ Construction management/testing consultants
______ Contractors
______ N/A

35. What is the final destination of the data collected utilizing handheld computers obtained on your projects during construction delivery.
_____ Do not know
_____ Project specific files kept by agency at resident level
_____ Project specific files kept by agency at central oversight level
_____ Database of all projects kept by agency at resident level
_____ Database of all projects kept by agency at central oversight levels
_____ Other, please specify: ___________________________________

36. What types of handheld computers are utilized on your projects during construction delivery? (Check all that apply.)
_____ PDA (personal digital assistant)
_____ Slate or tablet computer
_____ Small notebook computer
_____ Other, please specify: ___________________________________

37. In delivery of projects that have utilized handheld computers, what significance have the following factors had in contributing to the success of handheld computer implementation at your agency? [Select: High (1), Medium (2), Low (3), N/A (4).]

Cooperation/support of vendor/supplier	1	2	3	4
Comprehensive implementation plan	1	2	3	4
End-user training	1	2	3	4
Knowledge of expected benefits ease of use	1	2	3	4
Ease of use	1	2	3	4
In-house technical support	1	2	3	4

38. Please indicate handheld computer factors which contribute to success of use not listed in the previous question, and your level of satisfaction for each. [Select: High (1), Medium (2), Low (3), N/A (4).]

Other-1 1 2 3 4
Please describe application: ____

Other-2 1 2 3 4
Please describe application: ____

39. In your opinion, which of the following factors are involved in restricting handheld computer technology usage for construction project delivery in your agency? (Please mark all that apply.)
_____ Cost/agency budgeting
_____ Software interoperability issues
_____ Screens not viewable in direct sun
_____ Agency procedural issues
_____ Hardware durability
_____ End-user technical skill/training
_____ Conflicting technology standards
_____ Unawareness of benefits
_____ Slow data transfer/download
_____ Other, please specify: _______________________________________

40. Do you have any cost and/or benefit information on this technology?
Yes _____ No _____
Additional comments: ____
____

41. Has your agency written a specification or contract clause for this technology?
Yes _____ No _____
Additional comments: ____
____

PCC Temp/Maturity

42. May we follow up with a few clarifying questions?
Yes _____ No _____

43. On approximately how many projects per year has your agency utilized automated concrete temperature tracking and maturity monitoring in the delivery of construction projects?
_____ None (Please skip to Question 56.)
_____ 10 or less
_____ 10–30
_____ 30 or more
_____ Other, please specify number if known

44. For which types of construction is automated concrete temperature tracking and maturity monitoring utilized in the delivery of construction projects?
_____ Bridge
_____ Noise barrier/retaining walls
_____ Structures
_____ Paving
_____ Other, please specify: _______________________________________

45. Please indicate who of the project stakeholders utilized automated concrete temperature tracking and maturity monitoring technology in bridge construction.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

46. Please indicate who of the project stakeholders utilizes automated concrete temperature tracking and maturity monitoring technology in noise barrier/retaining wall construction.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

47. Please indicate who of the project stakeholders utilizes automated concrete temperature tracking and maturity monitoring technology in concrete structure construction.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

48. Please indicate who of the project stakeholders utilizes automated concrete temperature tracking and maturity monitoring technology in paving construction.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

49. Please indicate who of the project stakeholders utilizes automated concrete temperature tracking and maturity monitoring technology in other (Question 44) construction.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

50. In delivery of projects that have utilized automated concrete temperature tracking and maturity monitoring technology, what significance have the following factors had in contributing to the success of implementation at your agency. [Select: High (1), Medium (2), Low (3), N/A (4)]?

Cooperation/support of vendor/supplier	1	2	3	4	5
Cooperation/support of contractor	1	2	3	4	5
End-user training	1	2	3	4	5
Knowledge of expected benefits	1	2	3	4	5
Ease of use	1	2	3	4	5
In-house technical support	1	2	3	4	5

51. Please indicate any other factors beyond those listed in the previous question that have contributed to the success of automated concrete tracking and maturity implementation at your agency.

Other-1	1	2	3	4	5
Other-2	1	2	3	4	5

52. In your opinion, which of the following factors are involved in restricting automated concrete temperature tracking and maturity monitoring technology usage for construction delivery in your agency? (Please mark all that apply.)
_____ Cost (agency budgeting)
_____ Software interoperability issues
_____ Contract specification issues
_____ Agency procedural issues
_____ End-user technical skill/training
_____ Network/hardware maintenance
_____ Hardware durability
_____ Data acquisition
_____ Conflicting technology standards
_____ Unawareness of benefits
_____ Sensor placement
_____ Other, please specify: ___________________________________

53. Do you have any cost and/or benefit information on this technology?
Yes _____ No _____

54. Has your agency written a specification or contract clause for this technology?
Yes _____ No _____

55. May we follow up with a few clarifying questions?
Yes, prefer e-mail _____ Yes, prefer phone _____ No _____

4D CAD

56. On approximately how many projects per year has your agency utilized 4D CAD in the delivery of construction projects?
_____ None (Please skip to Question 72.)
_____ 10 or less
_____ 10–30
_____ 30 or more
_____ Other, please specify number if known __________

57. For which purposes and by whom is 4D CAD technology utilized in the delivery of construction projects? (Please check all that apply.)
_____ Materials fabrication and procurement
_____ As-built documentation
_____ Constructability review
_____ Communication of building methods/systems
_____ Public relations/outreach
_____ Other, please specify: ____

58. Please indicate who of the project stakeholders utilizes 4D CAD technology for material fabrication and procurement purposes.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

59. Please indicate who of the project stakeholders utilizes 4D CAD technology for as-built documentation purposes.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

60. Please indicate who of the project stakeholders utilizes 4D CAD technology for constructability review purposes.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

61. Please indicate who of the project stakeholders utilizes 4D CAD technology for communication of building methods/systems purposes.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

62. Please indicate who of the project stakeholders utilizes 4D CAD technology for quantity tracking purposes.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

63. Please indicate who of the project stakeholders utilizes 4D CAD technology for public relations purposes.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

64. Please indicate who of the project stakeholders utilizes 4D CAD technology for other (Question 57) purposes.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

65. For which types of projects is 4D CAD technology utilized in the delivery of construction projects? (Check all that apply.
_____ Design-build
_____ Design-build-bid
_____ Both design-build and design-build-bid
_____ Projects over a certain contract size (please specify): ____________
_____ Other, please specify: ____________________________________

66. In delivery of projects that have utilized 4D CAD modeling, what significance have the following factors had in contributing to the success of implementation at your agency? [Select: High (1), Medium (2), Low (3), N/A (4)]?

Cooperation/support of software application vendor/supplier	1	2	3	4	5
Comprehensive implementation plan	1	2	3	4	5
End-user training	1	2	3	4	5
Knowledge of expected benefits	1	2	3	4	5
Ease of use	1	2	3	4	5
In-house technical support	1	2	3	4	5
Cooperation of designers	1	2	3	4	5

67. Please indicate any other factors beyond those listed in the previous question that have contributed to the success of 4D CAD implementation at your agency. [Select: High (1), Medium (2), Low (3), N/A (4)]?

Other-1	1	2	3	4	5
Other-2	1	2	3	4	5

68. In your opinion, which of the following factors are involved in restricting 4D CAD modeling technology usage for construction delivery in your agency? (Please mark all that apply.)
_____ Cost (agency budgeting)
_____ Software interoperability issues
_____ Contract specification issues
_____ Agency procedural issues
_____ End-user technical skill/training
_____ Unawareness of benefits
_____ Non-cooperation of designers
_____ Conflicting technology standards
_____ Other, please specify: ____________________________________

69. Do you have any cost and/or benefit information on this technology?
Yes _____ No _____

70. Has your agency written a specification or contract clause for this technology?
Yes _____ No _____

71. May we follow up with a few clarifying questions?
Yes, prefer e-mail _____ Yes, prefer phone _____ No _____

WebCam

72. In 2005, how many projects utilized web-based video camera technology for remotely monitoring projects during construction?
_____ None (Please skip to Question 86.)
_____ All projects
_____ 10 or less
_____ Most projects when appropriate
_____ Other, please specify number if known ____________

73. For which purposes are web-based video cameras utilized in the delivery of construction projects? (Please check all that apply.)
_____ Website display of project
_____ Inspection purposes
_____ Time-phased image collection
_____ Legal purposes
_____ Other, please specify: ________________________________

74. Please indicate who of the project stakeholders utilizes web camera technology for website display of projects purposes.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

75. Please indicate who of the project stakeholders utilizes web camera technology for inspection purposes.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

76. Please indicate who of the project stakeholders utilizes web camera technology for time-phased image collection of project purposes.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

77. Please indicate who of the project stakeholders utilizes web camera technology for legal purposes.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

78. Please indicate who of the project stakeholders utilizes web camera technology for other purposes.
_____ Agency staff
_____ Construction management/testing consultants
_____ Contractors
_____ N/A

79. In delivery of projects that have utilized web-based video camera modeling, what significance have the following factors had in contributing to the success of implementation? [Select: High (1), Medium (2), Low (3), N/A (4)]?

Support of hardware application vendor/supplier	1	2	3	4	5
Support of software vendor/supplier	1	2	3	4	5
End-user training	1	2	3	4	5
Knowledge of expected benefits	1	2	3	4	5
Ease of use	1	2	3	4	5
In-house technical support	1	2	3	4	5
Comprehensive implementation plan	1	2	3	4	5

80. Please indicate any other factors beyond those listed in the previous question that have contributed to the success of web camera implementation at your agency. [Select: High (1), Medium (2), Low (3), N/A (4)]?

Other-1	1	2	3	4	5
Other-2	1	2	3	4	5

81. Please indicate the types of construction that web-based monitoring application(s) are the most beneficial? (Check all that apply.)
_____ Paving
_____ Bridge
_____ Utility location/relocation
_____ Mass grading
_____ Structure
_____ Other, please specify: ________________________________

82. In your opinion, which of the following factors are involved in restricting web camera technology usage for construction delivery in your agency? (Please mark all that apply.)
_____ Cost (agency budgeting)
_____ Software interoperability issues
_____ Hardware durability
_____ Agency procedural issues
_____ End-user technical skill/training
_____ Network/hardware maintenance
_____ Slow data transfer download
_____ Conflicting technology standards
_____ Unawareness of benefits
_____ Other, please specify: ____________________________________

83. Do you have any cost and/or benefit information on this technology?
Yes _____ No _____

84. Has your agency written a specification or contract clause for this technology?
Yes _____ No _____

85. May we follow up with a few clarifying questions?
Yes, prefer e-mail _____ Yes, prefer phone _____ No _____

86. [GPS] Is there information that you would like to add that was not covered by this questionnaire that you feel would benefit this study? (Please write your comments below.) ____
____
____

87. [Handheld PC] Is there information that you would like to add that was not covered by this questionnaire that you feel would benefit this study? (Please write your comments below.) ____
____
____
____

88. [PCC temp/maturity monitoring] Is there information that you would like to add that was not covered by this questionnaire that you feel would benefit this study? (Please write your comments below.) ____
____
____
____

89. [4D CAD] Is there information that you would like to add that was not covered by this questionnaire that you feel would benefit this study? (Please write your comments below.) ____
____
____
____

90. [Web camera] Is there information that you would like to add that was not covered by this questionnaire that you feel would benefit this study? (Please write your comments below.) ____
____
____
____

THANK YOU FOR YOUR HELP AND COOPERATION
Please return the completed questionnaire by March 31, 2006 to:
John J. Hannon (Consultant) or Brannon Myrick (Research Assistant)

APPENDIX B

Survey Responses

Agency	Survey Section				
	■ Complete □ Incomplete				
United States	GPS	HHC	PCC	4D CAD	CAM
Alabama Department of Transportation	■	■	■	■	■
Alaska Department of Transportation and Public Facilities	■	■	■	■	■
Arkansas State Highway and Transportation Department	■	■	■	■	■
California Department of Transportation	■	■	■	■	■
Colorado Department of Transportation	■	■	■	■	■
Connecticut Department of Transportation	■	■	■	■	■
Delaware Department of Transportation	■	■	■	■	■
Florida Department of Transportation	■	□	□	□	□
Georgia Department of Transportation	■	■	■	■	■
Hawaii Department of Transportation	■	■	■	■	■
Idaho Department of Transportation	■	■	■	■	■
Illinois Department of Transportation	■	■	■	■	■
Indiana Department of Transportation	■	■	■	■	■
Iowa Department of Transportation	■	■	■	■	■
Kansas Department of Transportation	■	■	■	■	■
Kentucky Transportation Cabinet	■	■	■	■	■
Louisiana Department of Transportation and Development	■	■	■	■	■
Maine Department of Transportation	■	■	■	■	■
Michigan Department of Transportation—1	□	■	□	□	□
Michigan Department of Transportation—2	■	■	■	■	■
Michigan Department of Transportation—3	□	■	■	□	□
Minnesota Department of Transportation	■	■	■	■	■
Mississippi Department of Transportation	■	■	■	■	■
Missouri Department of Transportation	■	■	□	■	□
Montana Department of Transportation	■	■	■	■	■
Nevada Department of Transportation	■	■	■	■	■
New Hampshire Department of Transportation	■	■	■	■	■
New Mexico Department of Transportation	■	■	■	■	■
New York State Department of Transportation	■	■	■	■	■
North Carolina Department of Transportation	■	■	■	■	■
North Dakota Department of Transportation	■	■	■	■	■
Ohio Department of Transportation	■	■	■	■	■
Oklahoma Department of Transportation	■	■	■	■	■
Oregon Department of Transportation	■	■	■	■	■
South Dakota Department of Transportation	■	■	■	■	■
Tennessee Department of Transportation	■	■	■	■	■
Texas Department of Transportation	■	■	■	■	■
Utah Department of Transportation	■	■	■	■	■
Vermont Agency of Transportation	■	■	■	■	■
Washington State Department of Transportation	■	■	■	■	■
West Virginia Department of Transportation	■	■	■	■	■
Wisconsin Department of Transportation	■	■	■	■	■
Wyoming Department of Transportation	■	■	■	■	■
Canada					
City of Vancouver	■	■	■	■	■
New Brunswick Department of Transportation	■	■	■	■	■
Nova Scotia Department of Transportation and Public Works	■	■	■	■	■
Ontario Ministry of Transportation	■	■	■	■	■
Prince Edward Island	■	■	■	■	■
Transports Quebec	■	■	■	■	■
Yellowknife, Northwest Territories	■	■	■	■	■

GPS = global positioning system; HHC = handheld computer; PCC = portland cement concrete; 4D CAD = four-dimensional computer-aided design; CAM = computer-aided manufacturing.

APPENDIX C

Agency Survey Responses of Technology Use

Agencies were credited with the use of a technology if they had incorporated it into at least one project or were conducting pilot project analysis.

Agency	Reported Technologies Applied				
	■ Use				
United States	GPS	HHC	PCC	4D CAD	CAM
Alabama Department of Transportation	■	■	■		
Alaska Department of Transportation and Public Facilities					■
Arkansas State Highway and Transportation Department		■			■
California Department of Transportation		■		■	■
Colorado Department of Transportation		■			
Connecticut Department of Transportation					
Delaware Department of Transportation	■				
Florida Department of Transportation	■				
Georgia Department of Transportation	■				■
Hawaii Department of Transportation			■		
Idaho Department of Transportation					
Illinois Department of Transportation	■	■			■
Indiana Department of Transportation	■		■		■
Iowa Department of Transportation	■	■	■		
Kansas Department of Transportation	■	■	■		
Kentucky Transportation Cabinet	■	■	■	■	
Louisiana Department of Transportation and Development		■			■
Maine Department of Transportation	■	■	■		■
Michigan Department of Transportation—1		■			
Michigan Department of Transportation—2	■	■	■		
Michigan Department of Transportation—3		■	■		
Minnesota Department of Transportation	■	■	■		■
Mississippi Department of Transportation			■		■
Missouri Department of Transportation	■	■			
Montana Department of Transportation	■	■	■		
Nevada Department of Transportation	■	■	■		■
New Hampshire Department of Transportation					■
New Mexico Department of Transportation	■	■			■
New York State Department of Transportation	■	■			
North Carolina Department of Transportation	■	■	■		
North Dakota Department of Transportation	■	■	■		■
Ohio Department of Transportation	■		■	■	■
Oklahoma Department of Transportation	■		■		
Oregon Department of Transportation					
South Dakota Department of Transportation	■	■			
Tennessee Department of Transportation	■				
Texas Department of Transportation	■	■	■		
Utah Department of Transportation	■	■			
Vermont Agency of Transportation	■	■	■		
Washington State Department of Transportation			■		
West Virginia Department of Highways	■				■
Wisconsin Department of Transportation	■	■	■		
Wyoming Department of Transportation	■			■	
Canada					
City of Vancouver		■			
New Brunswick Department of Transportation	■				
Nova Scotia Department of Transportation and Public Works	■				
Ontario Ministry of Transportation					
Prince Edward Island	■	■			
Transports Quebec	■		■		
Yellowknife, Northwest Territories	■			■	

GPS = global positioning system; HHC = handheld computer; PCC = portland cement concrete; 4D CAD = four-dimensional computer-aided design; CAM = computer-aided manufacturing.

APPENDIX D

Industrial Ratings and Standards for Mobile Computers

Ingress Protection (IP)

These protection standards are defined by the International Electrotechnical Commission and consist of rating scales designated by two to three digits (the third digit is commonly omitted). Symbol Technologies' SPT1800 Series Pocketable Computer specifies an IP54 rating. From the IP Code Digit Tables D1, D2, and D3, we can deduce that this device is dust and splash-water resistant.

It is important that manufacturers have their equipment certified by an outside laboratory to verify the product's IP rating. UL and CENELEC are two such laboratories, but many different laboratories exist that provide this service. The important thing is that the product is certified by an outside organization. If IP ratings are specified on a product's data sheet, then an approval certification number should also be included (e.g., EN 60 529 or Approved to IEC 529). Another important consideration is that every configuration of the product is IP certified, and not only one specific configuration. Many manufacturers will claim a certain IP rating, but this rating is only achieved with one specific and usually expensive configuration. All available configurations should be IP rated for proper protection to allow the customer flexibility when ordering a mobile computer (Crews 2004).

NEMA (National Electrical Manufacturer Association)

These ratings are applied to electrical fixed enclosures and their resistance to rigged conditions, not typically to handheld computers (HHCs). There is however a correlation between NEMA and IP ratings. The correlation is limited to dust and moisture ratings, but an understanding of them can aid in converting a NEMA rating to an IP rating (Crews 2006). Table D4 is the NEMA designation table, whereas Table D5 displays the correlation between the rating systems. It is important to note that Table D5 is useful for converting NEMA ratings to IP ratings, but not conversely.

TABLE D1
IP SPECIFICATION CODES DIGIT 1—PROTECTION AGAINST SOLID OBJECTS

First Digit	Rating
0	No special protection
1	Protection from a large part of the body such as a hand (but no protection from deliberate access); from solid objects greater than 50 mm in diameter
2	Protection against fingers or other object not greater than 80 mm in length and 12 mm in diameter
3	Protection from entry by tools, wires, etc., with a diameter of thickness greater than 1 mm
4	Protection from entry by solid objects with a diameter or thickness greater than 1 mm
5	Protection from the amount of dust that would interfere with the operation of the equipment
6	Dust tight

TABLE D2
IP SPECIFICATION TABLE DIGIT 2—PROTECTION AGAINST LIQUIDS

Second Digit	Rating
0	No special protection
1	Protection from dripping water
2	Protection from vertically dripping water
3	Protection from sprayed water
4	Protection from splashed water
5	Protection from water projected from a nozzle
6	Protection against heavy seas or powerful jets of water
7	Protection against immersion
8	Protection against complete, continuous submersion in water

TABLE D3
IP SPECIFICATION TABLE DIGIT 3—PROTECTION AGAINST MECHANICAL IMPACTS
(commonly omitted)

Third Digit	Rating
0	No special protection
1	Protects against impact of 0.225 joule (e.g., 150 g weight falling from 15 cm height)
2	Protects against impact of 0.375 joule (e.g., 250 g weight falling from 15 cm height)
3	Protects against impact of 0.5 joule (e.g., 250 g weight falling from 20 cm height)
4	Protects against impact of 2.0 joule (e.g., 500 g weight falling from 40 cm height)
5	Protects against impact of 6.0 joule (e.g., 1.5 kg weight falling from 40 cm height)
6	Protects against impact of 20.0 joule (e.g., 5 kg weight falling from 40 cm height)

TABLE D4
NEMA TYPE DESIGNATION TABLE

NEMA Rating	Intended Use and Description
1	Indoor use primarily to provide a degree of protection against limited amounts of falling dirt
2	Indoor use primarily to provide a degree of protection against limited amounts of falling water and dirt
3	Outdoor use primarily to provide a degree of protection against rain, sleet, wind-blown dust, and damage from external ice formation
3R	Outdoor use primarily to provide a degree of protection against rain, sleet, and damage from external ice formation
3S	Outdoor use primarily to provide a degree of protection against rain, sleet, wind-blown dust, and to provide for operation of external mechanisms when ice laden
4	Indoor or outdoor use primarily to provide a degree of protection against wind-blown dust and rain, splashing water, hose-directed water, and damage from external ice formation
4X	Indoor or outdoor use primarily to provide a degree of protection against corrosion, wind-blown dust and rain, splashing water, hose-directed water, and damage from external ice formation
5	Indoor use primarily to provide a degree of protection against settling airborne dust, falling dirt, and dripping noncorrosive liquids
6	Indoor or outdoor use primarily to provide a degree of protection against hose-directed water, the entry of water during occasional temporary submersion at a limited depth, and damage from external ice formation
6P	Indoor or outdoor use primarily to provide a degree of protection against hose-directed water, the entry of water during prolonged submersion at a limited depth, and damage from external ice formation
7	Indoor use in locations classified as Class I, Division 1, Groups A, B, C, or D hazardous locations as defined in the National Electric Code (NFPA 70) (commonly referred to as explosion proof)
8	Indoor or outdoor use in locations classified as Class I, Division 2, Groups A, B, C, or D hazardous locations as defined in the National Electric Code (NFPA 70) (commonly referred to as oil immersed)
9	Indoor use in locations classified as Class II, Division 1, Groups E, F, and G hazardous locations as defined in the National Electric Code (NFPA 70) (commonly referred to as dust-ignition proof)
10	Intended to meet the applicable requirements of the Mine Safety and Health Administration
12 and 12K	Indoor use primarily to provide a degree of protection against circulating dust, falling dirt, and dripping noncorrosive liquids
13	Indoor use primarily to provide a degree of protection against dust, spraying of water, oil, and noncorrosive coolant

MIL-STD (Military Standard) or MIL-SPEC (Military Specification)

These specifications are commonly used by governmental agencies for procurement of HHCs for use in military, public safety, emergency services, and maintenance operations. Specifically the MIL-STD 810F standard (available for viewing at: http://www.dtc.army.mil/navigator/) typically applies only to vibration and shock components of HHCs if specified by manufacturers. For significations of protection against liquid and solids, the consumer must rely upon the IP ratings (Crews 2004).

TABLE D5
NEMA TO IP SPECIFICATION
COMPARISON TABLE

NEMA No.	IP Designation
1	IP10
2	IP11
3	IP54
3R	IP14
3S	IP54
4 and 4X	IP56
5	IP52
6 and 6P	IP67
12 and 12K	IP52
13	IP54

Drop Specifications

Rugged computer manufacturers recommend specifications indicating the computer's ability to withstand the shock of a fall. The environment and mobility required on construction jobsites requires that tools be able to withstand typical drops from the hands, belt, and pocket. LXE Inc., a rugged computer manufacturer, suggests that an appropriate HHC for construction delivery be able to withstand a 4-ft drop onto concrete, regardless of which side or face of the device makes the first impact (Crews 2004).

Temperature Specifications

Operating and storage temperature specifications for construction site HHCs are an important variable for the protection of the hardware investment. Extreme outdoor temperatures as well as those inside work vehicles and jobsite trailers can have lethal effects upon consumer-grade devices. Some rugged computer devices contain built-in heaters and special coatings to minimize damage and malfunction from condensation moisture. Some ruggedized mobile computers carry specifications and ratings called I-Safe (Intrinsically Safe). These devices must carry a label with the I-Safe rating and the name of the NRTL testing lab (Nationally Recognized Testing Laboratory) that issued the rating. These ratings are commonly for use inside hazardous environments such as petrochemical plants (Crews 2004).

APPENDIX E

New York State Department of Transportation Engineering Bulletin: Preparation and Transfer of Electronic Data

To:

New York State Department of Transportation
ENGINEERING BULLETIN

EB
05-023

Expires one year after issue unless replaced sooner

Title: **PREPARATION AND TRANSFER OF ELECTRONIC ENGINEERING DATA**

Distribution: Manufacturers (18): Local Govt. (31): Agencies (32): Surveyors (33): Consultants (34): Contractors (39) ____________( )

Approved: /s/ Richard W. Lee__________________
Richard W. Lee, P.E., Director Design Services Bureau 4/5/05
Date

ADMINISTRATIVE INFORMATION:

Effective Date. This Engineering Bulletin (EB) is effective upon signature.
Superseded Issuances. None.

PURPOSE: To remind all involved in the design and/or delivery of Capital Projects for letting by the Department, of the guidance regarding the preparation and transfer of electronic engineering data.

TECHNICAL INFORMATION: The excerpts from Chapter 2 of the “CADD Standards and Procedure Manual” provided on pages 3 through 8 of this EB are being transmitted to remind project developers of the current guidance regarding the preparation and transfer of engineering data.

BACKGROUND: Construction Division, Regional Construction Groups, and contractors have been steadily increasing their use of CADD information to aid in the completion of construction contracts. CADD data has proven to be beneficial and has contributed to improvement in the quality of both project designs and field operations. This data is used during the design phases of a project to create project design alternatives, identify conflicts, ensure constructability, create plans, and determine quantity estimates. The use of this data on 3R, reconstruction, and new construction projects is increasingly more prevalent, thus warranting this reminder. As opposed to working with only paper contract documents and manual measurement practices, the following benefits result from the use of this data in construction:

- An increase in accuracy of measurements.
- A reduction in the number of quantity disagreements with the Contractor.
- A more efficient verification of the Contractor’s layout.
- The ability to print/plot plan sheets or portions of the project as needed in the field.
- A better understanding of information available and better record keeping.

There are numerous construction operations for which electronic engineering data can be used to help with the associated field engineering:

- Generate various reports (alignment, curves, baseline, utility pole locations, etc.).
- Stakeout reports and survey information.
- For any design element, get dimensions, station/offset, or elevation information that may not be labeled on the contract plans.
- Viewing and identifying utility conflicts or other conflicts that may not be shown on the contract plans.
- Perform earthwork volume calculations (cut/fill, stripping, benching, undercut, rock cut, etc.) for payment of work done under various pay items between any stations.
- Provide 3D modeling capabilities—earthwork slopes, excavations, abutments.
- Establish layout and volume calculations for footings and abutment walls, especially where they key into rock or are constructed in stages.
- Cut cross sections at any location and at any angle across the roadway.
- Clip out details or portions of the plans for inclusion on inspection reports or computation sheets.
- View the design in 3D and color.

- Turn on/off various information on the plans to better see the design elements or show information that was not displayed together on the paper contract documents.
- View project design overlaid on ortho-images of the project area.
- Perform drainage excavation/backfill volume calculations (along runs, around drainage structures, etc.).
- Determine milling areas by displaying the roadway perimeter and then calculating the square meters that will require milling.
- Eliminate the need to redraft plan sheets if there are significant redesign activities in the field.
- Draft electronic as-built plans using the design CADD files as a reference. Provides more flexibility/options than just drawing on paper copies.
- Get a visual flow line for where water will run along the roadway surface and at intersections (for verifying proposed locations for drainage inlets).
- Perform field edits to the project design.
- Provide this information to the Contractor, utility company, or municipality.

Typical problems encountered in the electronic data for some projects, which should be avoided, include:

- Files that do not conform to the file naming convention.
- MicroStation files that contain a combination of elements used for creating plan sheets, details, cross sections, profiles, and/or copies of outdated sheets, or project alternatives all in the same file. To effectively work with, share, and transfer information, it should be organized consistent with the “CADD Standards and Procedure Manual.”
- MicroStation files in which proposed mapping is not drawn in its coordinated location in State Plane Coordinates. For projects that have existing mapping (i.e., Photogrammetry or Survey) in State Plane Coordinates available, proposed mapping should be drawn in the coordinated location in State Plane Coordinates.
- Proposed DTMs that do not include side slopes that reflect cut and fill limits shown in contract plans.
- Proposed DTMs where the pavement elevations, widths, or superelevation does not match contract plans.
- Proposed DTMs where intersecting roadways are not included, intersections do not tie vertically into the mainline, or where transverse roadway features (curb, ditches, sidewalks, etc.) run through intersections.

The following excerpts from Chapter 2 of the “CADD Standards and Procedure Manual” are current guidance regarding the transfer and format requirements of electronic information:

CHAPTER 2
FILE FORMAT AND TRANSFER REQUIREMENTS

2.2 SUBMISSIONS OF ELECTRONIC INFORMATION

Requirements for the submissions of electronic information are as follows:

1. The supplier shall provide the customer with the information, in electronic format, described below in items a through g. **The supplier shall use MicroStation® and InRoads Civil Suite® to create all files submitted as outlined**. (MicroStation and InRoads Civil Suites are registered trademarks of Bentley Systems.)

a. The supplier shall submit graphic files in MicroStation (.DGN) format. All CADD graphic files shall be created using MicroStation. Files that are .DXF, .DWG, .IGES, etc., are not acceptable formats.
b. The supplier shall submit surface files in InRoads Digital Terrain Model (.DTM) format. All DTM files shall be created using InRoads Civil Suite.
c. The supplier shall submit alignment and coordinate geometry point data for all existing features in an InRoads alignment file (.ALG) format. All ALG files shall be created using InRoads Civil Suite.
d. Record plan alignments shall be submitted in InRoads alignment file (.ALG) format. All ALG files shall be created using InRoads Civil Suite.
e. Right-of-way, property, highway boundary lines, or horizontal control shall be submitted in InRoads alignment file (.ALG) format. All ALG files shall be created using InRoads Civil Suite.
f. Text file(s) listing all survey data collected for the project shall be in ASCII format.
g. There are additional requirements for electronic information submitted to the Structures Division. These requirements are outlined in the Bridge Data Sheets and listed in the "Bridge Manual" Appendices 3A and 3B.

2. Consultant suppliers shall submit files through the Department's ProjectWise System. Consultant suppliers obtain access to the ProjectWise System by requesting an account through their Project Manager/Job Manager/Consultant Manager as applicable.
3. Department suppliers shall submit files to Department customers through the use of ProjectWise.
4. All files shall be checked for computer viruses before submission. The supplier shall include a dated log file and a written verification of this virus check, which includes the name of the virus check software and version number used and the date the virus check was done. Files that contain viruses are not acceptable.
5. For every project a transmittal letter to the customer shall be prepared that includes a listing of what is being submitted to the customer. This transmittal letter shall be included in the appropriate ProjectWise folder the files are added to; and sent to the appropriate Project Manager/Job Manager/Consultant Manager. The listing shall include file names, the Project Identification Number (PIN), official job title, State Highway Number(s), and reference marker numbers for the beginning and ending locations contained within the files. The listing shall also include a reference between file name and plan drawing numbers. The submission shall also be numbered and dated; e.g., Submission #1, 12/22/2003. Revisions shall be submitted under the original submission number and include a revision number and revision date.
6. All submissions shall be compatible with the current versions of CADD software in use by NYSDOT as designated in an annually issued Engineering Bulletin.
7. Department suppliers shall use approved versions of CADD software. Consultant suppliers shall use approved versions of MicroStation and InRoads Civil Suite.
8. Consultant suppliers may submit electronic files in other than the stated versions of NYSDOT CADD software standards, as long as the files are compatible with NYSDOT CADD software standards. A written request shall be sent to NYSDOT stating the version of the NYSDOT CADD software standard the consultant supplier is requesting to use for the submission. This request shall be directed to and approved by the Project Manager/Job Manager/Consultant Manager as applicable.
9. The supplier shall ensure that the contents of all electronic files are the same as any hard copy information submitted (e.g., survey notes or paper plots).
10. The supplier shall name the files as stated in Chapter 3 of this manual.

2.3 INFORMATION AVAILABLE FROM NYSDOT

NYSDOT does not guarantee the accuracy or performance resulting from the use of shared computer programs or files including direct, indirect, special, or consequential damages. No technical support shall be provided. No warranties are extended or granted, either expressed or implied, with respect to the accuracy and/or performance of any materials provided.

Department and Consultant suppliers shall use NYSDOT support files discussed in this manual. Support files referenced throughout this manual are available. Consultant suppliers should obtain these support files from the Department's Public Web site, at the following location, http://www.dot.state.ny.us/caddinfo/caddinfo.html. Department suppliers obtain support files referenced throughout this manual through NYSDOT's network. Department suppliers working in off-network locations may obtain these files by contacting the Design Services Bureau at (518) 457-6685. Available resource information is outlined in Chapter 4.

2.4 GRAPHIC FILE REQUIREMENTS

Requirements for all graphical CADD files are as follows:

1. All graphic files submitted shall be in a MicroStation (.DGN) format. **The supplier shall use MicroStation for all graphical CADD work being submitted**. All graphic files shall conform to applicable chapters in this manual. Any questions regarding items not included in this manual, or interpretations of this manual should be addressed to the CADD Innovation Section of the Design Services Bureau. Consultant suppliers should direct questions regarding interpretations of this manual to the CADD Innovation Section through the Project Manager/Job Manager/Consultant Manager as applicable.
2. All text shall conform to the requirements outlined in Chapter 5 of this manual.
3. All text shall be placed view dependent.
4. Text shall be readable from left to right or bottom to top of the final printed drawing.
5. The supplier shall not submit any files with B-Spline curves.

Sections 2.4.1, 2.4.2, and 2.4.3 contain graphic file requirements for existing information, proposed information, and detail drawings and tables.

2.4.1 Existing Information

All graphic files containing existing project information shall be transmitted from the supplier (Regional Survey Group, Photogrammetry Section, Regional ROW Mapping, or consulting firm, etc.) to the customer (Regional or Main Office Design Group, or consulting firm, etc.) conforming to the following requirements:

1. All topography or base mapping files shall consist of graphic elements representing the existing topography as obtained for the purpose of the survey. Topography shall be drawn in its coordinated location using the State Plane Coordinate System.
2. All features represented by linear or curvelinear elements shall be drawn using 3D Line strings or 3D Curve strings.
3. All topographic symbols shall be placed using cells from the applicable ny_plan (contents).cel cell library or with line styles from the ny_linestyle_2003.rsc custom line resource file. Cells and line styles shall be placed at an active scale of 1 for a 1:100 scale D size plot. Scale factor adjustments shall be made for files mapped at scales other than a 1:100 scale; e.g., an active scale of 2.5 for files mapped at a scale of 1:250 for a D size plot.
4. Any baseline alignments, centerline alignments, highway boundary lines, property lines, profiles, and cross sections shall be placed at elevation zero. The distance between station marks for alignments shall be accurate to three decimal places.
5. The following information is provided for the development of the graphic file(s):
    a. All text is to be placed with attributes as stated in Chapter 4 of this manual.
    b. All text shall be placed at either elevation zero or at an elevation equal to that of the feature it is describing.
    c. Text strings shall not overlap each other so that they become unreadable on a plot with all of the levels displayed. Point numbers for surveyed points may overlap.
    d. A line string in the topography file shall never be broken to make a text string easier to read. If necessary, place the text string off to the side and use a leader line to point to the location of the feature.
    e. The legend sheet should be as shown in Chapter 21 of the "Highway Design Manual" or the latest revision available in the ny_sheet.cel cell library. If the supplier needs to add additional features not provided on the legend sheet, they must submit a modified legend sheet outlining these features to the Project Manager/Job Manager/Consultant Manager as applicable. Features designated on the legend sheet shall not be altered.
6. Either sign faces or a description of each sign shall be placed with the existing topography.
7. a. If the supplier chooses to show sign faces, they should be displayed using the ny_plan_signs.cel cell library.
    b. Standard "Manual of Uniform Traffic Control Devices" signs shall show the sign face.
    c. Nonstandard signs and guide signs, such as business signs, shall have measurements indicating the sign size. The actual face may be drawn or a description of the wording on the sign is acceptable.
8. The supplier shall submit a separate graphic file(s) that contains the point numbers and feature coding for all surveyed points. This file shall be a reference attached to the topography file.

2.4.2 Proposed Information

All graphic files containing proposed project information shall be transmitted from the supplier (Regional or Main Office Design Group, Main Office Structures Group, ROW Mapping, other functional group, or consulting firm, etc.) to the customer (Regional Construction Group, Main Office Design Group, Main Office Structures Group, etc.) conforming to the following requirements:

1. All proposed mapping files shall consist of graphic elements representing the proposed topography as designed. Proposed mapping graphics shall be drawn in their coordinated location using the State Plane Coordinate System.
2. Graphic files shall be true three-dimensional (3D) files.
3. The supplier shall submit a proposed break line file that accurately represents the proposed condition of the project after construction. The proposed break line file shall be created in such a way that an accurate Digital Terrain Model could be created from graphical elements alone, and this file shall include an exterior boundary of the proposed work.
4. Centerline alignments, property lines, right-of-way lines, profiles, and cross sections shall be placed at elevation zero.

2.4.3 Detail Drawings and Tables

All graphic files containing proposed detail drawings and tables shall be transmitted from the supplier (Regional or Main Office Design Group, Main Office Structures Group, ROW Mapping, other functional group, or consulting firm, etc.) to the customer (Regional Construction Group, Main Office Design Group, Main Office Structures Group, etc.) conforming to the following requirements:

1. All details shall be drawn with scales labeled as stated in Chapter 5.
2. All tables shall be generated using fonts as outlined in Chapter 5.

2.5 SURFACE FILE REQUIREMENTS

2.5.1 Existing Features

All surface files containing existing project information shall be transmitted from the supplier (Regional Survey Group, Photogrammetry Section, or consulting firm, etc.) to the customer (Regional or Main Office Design Group, or consulting firm, etc.) conforming to the following requirements:

The supplier shall submit a surface file that is an InRoads Digital Terrain Model in the **Digital Terrain Model (.DTM)** format. All DTM files shall be created using Bentley's InRoads Civil Suite. This file shall be representative of the existing ground at the time of the survey/mapping and shall have been field edited. This file shall be feature based, using the feature/code names as stated in Chapter 4 of this manual. The file shall be created in a way that the graphics resulting from a display of the features is identical to the base mapping as stated in Section 2.4.1.
If a project contains one or more bridges, supplemental Digital Terrain Models (DTMs) shall be provided for each bridge deck surface.
If the surveyed area includes an undercut area or overhang area, supplemental DTMs shall be created to accurately portray the field conditions.

2.5.2 Proposed Features

All surface files containing proposed project information shall be transmitted from the supplier (Regional or Main Office Design Group, Main Office Structures Group, or consulting firm, etc.) to the customer (Regional Construction Group, etc.) conforming to the following requirements.

1. The supplier shall submit surface files that are InRoads Digital Terrain Model in the **Digital Terrain Model (.DTM)** format. All DTM files shall be created using Bentley's InRoads Civil Suite. The surface file(s) shall be the proposed ground as designed in the contract plans. These files shall be feature based, using the feature/code names as stated in Chapter 4 of this manual. These files may be used to develop cross sections, profiles, and quantities during the construction of the project. All Digital Terrain Models (DTMs) shall be developed using the following requirements:
    a. The point density interval for break line features shall be set to no more than 10 m to allow for a sufficiently dense proposed surface. The point density interval for break line features on bridge decks or culvert walls should be less than 10 m. Areas with several features, such as curbed areas, intersections, and areas of tight vertical curvature may require a smaller point density interval to accurately represent the proposed surface.
    b. A Maximum Triangle Length shall be set so that triangles do not make erroneous connections.
    c. Surfaces shall include a perimeter. Inaccurate or extraneous triangles around the perimeter of the proposed ground shall be deleted. Inaccurate triangles include any surface information that does not reflect the actual intended proposed work.
    d. Problems encountered when building the surface file shall be corrected by fixing the features in the DTM file, rather than by modifying or deleting a point used to create a triangle vertex.
    e. Proposed DTM files shall be feature based, using the feature/code names as stated in Chapter 4 of this manual. These files shall be created in a way that the graphics resulting from a display of the features is identical to the proposed mapping as stated in Section 2.4.2.

2.6 ADDITIONAL FILE REQUIREMENTS

All additional files containing coordinate geometry, survey information, and alignment information shall be transmitted from the supplier (Regional Survey Group, Photogrammetry Section, Regional ROW Mapping, or consulting firm, etc.) to the customer (Regional or Main Office Design Group, or consulting firm, etc.) conforming to the following requirements:

Additional file requirements are as follows:

1. The supplier shall provide alignments and coordinate geometry points of existing survey. If the supplier is required to provide record plan alignments for the project, alignments shall be entered using coordinate geometry points or computed values rather than picking points from the graphic file. These coordinates of all points and computed values shall be input to four (4) decimal places.
2. The supplier shall submit an ASCII file that contains a list of all of the surveyed points. This file shall meet the following requirements:
    a. It shall be in a linear format with no more than one point on each line of the file.
    b. Each line shall contain the point number, an X, Y, and Z coordinate, feature coding, and a short description of the surveyed point.
    c. Each description shall be readily identifiable using the Feature/Code Names designated in Chapter 4 of this manual.
3. The supplier shall submit an ASCII file that contains a list of all final right-of-way and property line points.
4. The supplier shall submit proposed alignment files that include any and all horizontal control, vertical control, and superelevation shown on the contract plans. Geometry shall utilize Geometry Styles stated in Chapter 4. Geometry information that may have been used during the course of design, but is not part of the contract plans, should be removed from the proposed alignment file prior to submitting the file to the customer.

CONTACT: Questions regarding this EB may be directed to Susan Andrews of the Design Services Bureau at (518) 457-6685 (e-mail: sandrews@dot.state.ny.us).

APPENDIX F

Annotated Bibliography

3D–4D Building Information Modeling, U.S. General Services Administration, Washington, D.C., 2006 [Online]. Available: http://www.gsa.gov/Portal/gsa/ep/contentView.do?contentType=GSA_OVERVIEW&contentId=20917&noc=T [accessed May 18, 2006].

In 2003, GSA established the 3D-4D-BIM (Building Information Modeling) Program. GSA has initiated 10 pilot projects in its current capital program, while assessing and supporting 3D-4D-BIM applications on more than 20 ongoing projects across the nation. The power of visualization, coordination, simulation, and optimization from 3D, 4D, and BIM computer technologies allow GSA to more effectively meet customer, design, construction, and program requirements. GSA is committed to a strategic and incremental adoption of 3D-4D-BIM technologies.

Abler, F., "Expressive 3D Components for Building Simulation and BIM," *AECbytes Viewpoint*, May 25, 2006.

The transfer of sophisticated Non-Photo Realistic rendering technology from the entertainment industry (animation and video games) to the Architecture, Engineering, and Construction (AEC) industry will have far-reaching effects on building simulation and on data-driven BIM.

Akbaş, R., *Geometry-Based Modeling and Simulation of Construction Processes*, 2003 (presentation slides), Paper read at Intelligent and Automated Construction Job Site Workshop, Dec. 16, 2003.

Akbaş, R., *Geometry-Based Modeling and Simulation of Construction Processes*, CIFE Technical Report #151, Ph.D. dissertation, Department of Civil Engineering and Environmental Engineering, Stanford University, Stanford, Calif., 2004.

Akinci, B., *Advanced Sensor-Based Defect Detection and Management at Construction Sites* (*ASDMCon*), presentation slides, 2003.

Akinci, B., *Position Paper: Lessons Learned from Using Sensing Technologies for Active Project Quality Control*, FIATECH, University of Texas at Austin, n.d.

Case studies and pilot tests on construction sites show that Laser Detection and Ranging (LADAR), RFID, and embedded temperature sensor technologies are mature enough and can be readily deployed on construction sites.

Akinci, B., "Using Sensor Systems and Standard Project Models to Capture and Model Project History for Building Commissioning and Facility Management," In *Facility Area Network Workshop,* Civil Engineering Research Lab (CERL), Champaign–Urbana, Ill., 2004.

Advances in sensor and tagging systems provide a way to capture the as-built history of a construction project to be utilized during facilities management. Recent developments in generating 3D environments using laser scanning technologies, and in acquiring quality information about built environments using embedded and other advanced sensors, create an opportunity to explore the feasibility of frequently gathering complete and accurate 3D and quality-related as-built data throughout the construction and facility management phases of a project.

Akinci, B., M. Patton, and E. Ergen, "Utilizing Radio Frequency Identification on Precast Concrete Components—Supplier's Perspective," Presented at the 19th International Symposium on Automation and Robotics in Construction (ISARC), Sep. 23–25, 2002, Washington, D.C.

Precast concrete material suppliers are responsible for the components that they manufacture from casting until up to 25 years after installation. To effectively manage the production and storage at the production facility, to streamline the construction process, and to quickly repair a component should a problem arise, information about components must be readily available and updated throughout the 25-year life cycle. Currently, suppliers use barcodes to track precast components and paper-based documents to store information about them. These approaches are time-consuming and error-prone. Suppliers also face the problem of not finding the right information in a timely manner. This paper discusses the utilization of RFID technology for tracking precast concrete components and their historical information from fabrication to post-construction. RFID is an automatic identification technology that uses memory chips attached or embedded to objects to transmit data about them. The discussion revolves around one use case developed to describe the current component tracking approach and the proposed approach utilization of RFID technology from a large-scale precast manufacturer/erector's perspective. The conclusion contains an assessment of benefits and limitations of the proposed utilization of RFID system for tracking precast concrete materials.

Akinci, B., S. Staub, and M. Fischer, "Productivity and Cost Analysis Based on a 4D Model," *Construction Informatics Digital Library*, 1997 [Online]. Available: http://itc.scix.net/data/works/att/w78-1997-23.content.pdf.

4D CAD models are being used more and more frequently to visualize the transformation of space over time. To date, these models are mostly purely visual models. Any evaluation of a 4D model; for example, whether it presents a workable construction sequence, is left to the viewer. The evolution of 4D CAD demonstrates the ability to provide a tighter link between visualization and analysis tools. This paper discusses how an intelligent 4D model helps identify time–space conflicts between concurrent activities and provides assistance in calculating more realistic cost estimates. The 4D system (4D Work Planner) presented here is based on symbolic and graphic product and process models, and provides both the visual and analytical feedback necessary to reengineer construction sequences.

An Investigation of the Use of Global Positioning System (*GPS*) *Technology and Its Augmentations Within State and Local Transportation Departments*, Federal Highway Administration, Washington, D.C., 2000.

This report summarizes the results of an investigation conducted by FHWA's Office of Operations Research in conjunction with the Turner–Fairbank Highway Research Center. This investigation targets the evolving character of applications using global positioning system (GPS) technology and its augmentation for surface transportation, especially highway departments, on the state and local level.

A.R.M. System Technical Specifications, OxBlue Corporation, Atlanta, Ga., n.d.

Marketing/technical specifications: OxBlue ARM Systems webcams.

Automated Citation Solutions—Symbol Technologies, Holtsville, N.Y., 2003.

Throughout the world, most law enforcement citations issued by police officers or officials for traffic or other minor violations are handwritten. After issuance, the citations (also called tickets, violation notices, or infringement notices) are then manually entered into multiple databases using a key-based system. These manual handwriting-based systems are extremely prone to data entry errors or misinterpretation as a result of illegible writing.

Bacon, S., "Maine DOT Finds Success with Portland Connector," *Constructor Magazine—A Publication of the AGC*, Mar./Apr. 2006.

The Maine DOT's use of design-build on construction of the $25 million Portland Connector, which links the Outer Congress Street exit of Interstate 295 with West Commercial Street and Portland's working waterfront, enabled the project team to bring the roadway to completion nearly 2 years earlier than what would have been expected under traditional design-bid-build. Before road construction started, Shaw Bros. used a satellite GPS to perform the majority of the layout and grading of the site, cutting surveying time by at least 50% and greatly reducing the possibility of human error, says John Allen, the firm's grade layout foreman. Surveyors used real-time kinematic GPS to take measurements, a system relatively new to highway construction applications, which provided a 95% confidence level within an inch on horizontal measurements.

Baker, D., Virtual Construction—Presentation slides, Turner Corporation, New York, N.Y., 2003 [Online]. Available: www.fiatech.org/pdfs/pastpres/roadmap/Turner.pdf.

Behzadan, A.H. and V.R. Kamat, "Visualisation of Construction Graphics in Outdoor Augmented Reality," Presented at the 2005 Winter Simulation Conference, Piscataway, N.J., Dec. 4–7, 2005.

This paper describes research that investigates the application of Augmented Reality (AR) in 3D animation of simulated construction operations. The objective is an AR-based platform that can be used together with corresponding equipment (HMD, GPS receiver, and a portable computer) to generate a mixed view of the real world and superimposed virtual simulation objects in an outdoor environment. The characteristic that distinguishes the presented work from indoor AR applications is the capability to produce real-time updated output as the user moves around, while applying minimum constraints over the user's position and orientation. The ability to operate independently of environmental factors (e.g., lighting conditions and terrain variations) makes the described framework a powerful tool for outdoor AR applications. This paper presents initial results and an AR platform prototype (UMAR-GPS-OVER) that is able to place 3D graphical objects at any desired location in outdoor augmented space.

Bertini, R.L. and A. Byrd, Custom Transportation Data Collection Software for Handheld Computers: Draft Whitepaper, 2003 [Online]. Available: http://www.its.pdx.edu/pdf/PALM_TRB.pdf.

In an effort to facilitate data collection for research and give students first-hand experience collecting data for class projects, the Portland State University Intelligent Transportation Systems (ITS) Laboratory has developed custom data collection software for PalmOS HHCs. The software is designed to allow exporting the collected data to desktop computers in common file formats suitable for analysis in spreadsheet and geographic information systems (GIS) applications. Data collection problems addressed include recording position over time, recording the geographic location of features, and performing cumulative vehicle counts.

Bingley, L., "GPS Users Must Plan for Outages," *IT Week: VNU Business Publications*, 2005 [Online]. Available: http://www.itweek.co.uk/itweek/news/2142864/gps-users-plan-outages.

Firms that rely on the U.S. GPS should ensure that they have a fallback plan, as one of the United Kingdom's top navigation experts has warned that the system may prove unreliable.

Blickenstorfer, C.H., "Definitions and Specifications: Rugged Enough?" *Rugged PC Review*, 2006 [Online]. Available: http://www.ruggedpcreview.com/3_definitions_what_is_rugged.html.

Although there are a variety of testing methods and ratings, there is no single entity that manages, monitors, and enforces a set of ruggedness standards for mobile computers. As a result, the term "rugged" is relative. Just because a manufacturer describes a device as rugged does not necessarily mean that it fills your particular needs. Any rugged device has likely been reinforced to some extent and will offer some extra protection; however, users will need to review it to know what the listed ruggedness specifications mean, and probably ask a number of questions.

Bowden, S. and A. Thorpe, "Mobile Communications for On-Site Collaboration," *Proceedings of ICE Civil Engineering*, Nov. 2002.

The construction industry's drive toward using information and communications technology to enhance collaborative working seems to have left site staff behind. This paper examines the information needs of site staff and shows that there are several technology solutions currently available to support them. Based on a recent site trial, it also shows that, contrary to general perceptions, site staff is more than ready to adopt modern technology and should be included in all future strategies for collaboration systems.

Bowden, S.L., "Application of Mobile IT in Construction," Engineering Doctorate (EngD), Department of Civil and Building Engineering, Loughborough University, Loughborough, United Kingdom, 2005.

In recent years, the construction industry has been compelled to explore all possible options for improving the delivery of their products and services. Clients are now expecting better service and projects that meet their requirements more closely. This has challenged the industry to become more efficient, integrated, and more attractive, with benefits for its potential workforce and for society as a whole. Information and communication technologies (ICT) are an enabler to facilitate the improvements required for modernization. However, owing to the geographically dispersed and nomadic nature of the construction industry's workforce, many individuals are prevented from efficiently and effectively using the ICT tools adopted to date. Mobile technologies providing the "last mile" connection to the point of activity could be the missing link to help address the ongoing drive for process improvement. Although this has been a well-researched area, several barriers to mainstream adoption still exist including (1) a perceived lack of suitable devices; (2) a perceived lack of computer literacy; and (3) the perceived high cost. Through extensive industry involvement, this research has furthered the theoretical idea that mobile IT use in the construction industry would be beneficial; demonstrating by means of a state-of-the-art assessment, usability trials, case studies, and demonstration projects that the barriers to mainstream adoption can be overcome. The findings of this work have been presented in four peer-reviewed papers. An ongoing dissemination program is expected to encourage further adoption.

Bowden, S.L., A. Dorr, A. Thorpe, and C.J. Anumba, "Mapping Site Processes for the Introduction of Mobile IT," Presented at the European Conference on Products and Processes Modelling (ECPPM 2004), Istanbul, Turkey, Sep. 8–11, 2004.

Owing to its nature, the construction industry requires its personnel to be mobile; to communicate efficiently; and to exchange, analyze, and synthesize large volumes of information. The construction industry's drive towards utilizing IT to enhance communication—both within a company and between clients, consultants, contractors, subcontractors, and suppliers—has, to date, largely ignored the need to deliver information effectively to mobile personnel (e.g., while on site or attending a client meeting). The advent of suitable devices and software solutions will go some way to correct this. However, simply because the technology is now available it should not be indiscriminately applied. This paper documents activities undertaken to better understand which construction processes would derive the most benefit from the application of mobile information and communication technologies. The approach taken also illustrates how these processes link together, thus providing an optimum implementation plan for mobilizing site-based processes. This research forms part of a larger study (known as COMIT).

Bowman, D., *Software Tools and the Future*, Bentley Civil, Washington, D.C., 2006, presentation slides.

Brettmann, T., T. Posey, and R. Sallee, *Evaluation of Grout Strength Gain Within Augered Cast-in-Place Piles Using Concrete Maturity Meter*, n.d.

The rate of strength gain for concrete or grout is essential information when determining the load-carrying capacity of a recently

placed structure. New technology in maturity meters allows for embedded components to be used in lieu of external recording devices, making the use of these instruments more feasible on jobsites. This paper presents the results of strength gain data collected from grout used to construct augered cast-in-place (ACIP) piles for load testing and production on a Houston-area project. Strength gain within the ACIP piles was evaluated using an Engius IntelliRockä Maturity Meter that had been calibrated using standard ASTM procedures for compressive strength testing of grout cubes and cylinders for the grout mix design used in construction.

Brown, C., *GPS and DOT*, AASHTO Technology Implementation Group, Washington, D.C., n.d., presentation slides.

Brown, C. and L. Anderson, *The Use of GPS in the Departments of Transportation*, n.d., presentation slides.

Brown, D., "Stakeless and Stringless: Automated Grading Controls Progress," *Grading & Excavation Contractor*, May/June 2002.

Contractors nationwide are discovering automatic grade-control systems as a way to do fine grading without stakes, stringlines, or grade checkers. These new systems offer a choice of sensors to automate blade and cutter controls on earthmoving machines.

Bryden, P. and R. Luther, "Handheld Computers: Replacing Clipboards and Field Books," *Atlantic Construction Journal*, 2005 [Online]. Available: http://ctca.unb.ca/CTCA/communication/handheldcomputers.htm [accessed April 18, 2005].

Caldas, C.H., C.T. Haas, D.G. Torrent, C.R. Wood, and R. Porter, "Field Trials of GPD Technology for Locating Fabricated Pipe in Laydown Yards," FIATECH, University of Texas at Austin, 2004.

The pilot trial reported here assessed the potential of GPS technology to improve the tracking and locating of tagged materials, specifically fabricated pipe spools, in construction laydown storage. Although industry research focus has been primarily on materials management, materials handling procedures on the construction site have been relatively unexamined, and presents potential for significant improvement.

"Can Your Rugged Wireless Computer Really Handle That?" In *Whitepaper*, LXE, Inc., Norcross, Ga., 2003

Once a very small portion of the mobile computing market, demand for industrial-strength, rugged, mobile computers is growing at a rapid rate. Industrial customers are realizing that high repair and replacement costs of non-industrial-strength computers, along with the decrease in productivity associated with down time can greatly decrease profitability. Every day, more and more vendors claim to have "ruggedized" computers. But how can you tell how rugged a terminal really is? This paper identifies the common specifications used to "describe" the ruggedness of a mobile computer and clarifies what each of these specifications truly mean. The paper also discusses the design characteristics to look for to determine a product's true capabilities and limitations. Just because a terminal looks rugged does not mean that it is rugged.

Carino, N.J., *Nondestructive Testing of Concrete: History and Challenges*, American Concrete Institute, Detroit, Mich., 1994.

A brief history of nondestructive testing of hardened concrete over the past 50 years is presented. The contributions of V.M. Malhotra toward the development and promotion of nondestructive testing are emphasized. The underlying principles and inherent limitations of the methods are reviewed, and historical highlights of their development are presented. Test methods are grouped into those that assess in-place strength and those that evaluate nonstrength characteristics, such as flaws and deterioration. The paper concludes with a discussion of the challenges for the 21st century in the area of nondestructive testing.

Carino, N.J., "Nondestructive Test Methods," Chapter 19, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, Md., 1997 [Online]. Available: http://www.fire.nist.gov/bfrlpubs/build98/PDF/b98019.pdf.

Carino, N.J., and H.S. Lew, "The Maturity Method: From Theory to Application," *Proceedings of the 2001 Structures Congress & Exposition*, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, Md., 2001.

The maturity method is a technique to account for the combined effects of time and temperature on the strength development of concrete. The method provides a relatively simple approach for making reliable estimates of in-place strength during construction. The origin of the method can be traced to work on steam curing of concrete carried out in England in the late 1940s and early 1950s. As a result of technology transfer efforts by the FHWA, there is renewed interest in the method in the United States. The purpose of this paper is to review the basic concepts underlying the method and to explain how the method is applied. The review focuses on work carried out by researchers at the National Institute of Standards and Technology (formerly the National Bureau of Standards).

Case Study: 4th Avenue Jail Project, Phoenix, Arizona, n.d., *Engius Construction Intelligence Case Studies*, Stillwater, Okla., n.d. [Online]. Available: http://www.engius.com/publications/casestudies/McCarthy%20Case%20Study.pdf.

Case Study: City of Wichita, Kansas, *Engius Construction Intelligence Case Studies*, Stillwater, Okla., n.d. [Online]. Available: http://www.engius.com/publications/casestudies/Pavers%20Inc%20Case%20Study.pdf.

Case Study: Cold Weather Paving Project Interstate 30, Little Rock, Arkansas, *Engius Construction Intelligence Case Studies*, Stillwater, Okla., n.d. [Online]. Available: http://www.engius.com/publications/casestudies/Duit%20I-30%20Case%20Study.pdf.

Case Study: Courtyard by Marriott, Oklahoma City, Oklahoma, *Engius Construction Intelligence Case Studies*, Stillwater, Okla., n.d. [Online]. Available: http://www.engius.com/publications/casestudies/Flintco%20Courtyard%20Marriott%20Case%20Study.pdf.

Case Study: Dallas High-Five Interchange Project, Dallas, Texas, *Engius Construction Intelligence Case Studies*, Stillwater, Okla., n.d. [Online]. Available: http://www.engius.com/publications/casestudies/Zachry%20Dallas%20Hi5%20Case%20Study.pdf.

Case Study: I-10 Hurricane Damage Reconstruction, *Engius Construction Intelligence Case Studies*, Stillwater, Okla., n.d. [Online]. Available: http://www.engius.com/publications/casestudies/I10%20Rebuild%20SHT-%20intelliRock.pdf.

Case Study: Interstate 40 Bridge Reconstruction, Webbers Falls, Oklahoma, *Engius Construction Intelligence Case Studies*, Stillwater, Okla., n.d. [Online]. Available: http://www.engius.com/publications/casestudies/I-40%20Case%20Study.pdf.

Case Study: Interstate 65 Paving Project, Indiana, *Engius Construction Intelligence Case Studies*, Stillwater, Okla., n.d. [Online]. Available: http://www.engius.com/publications/casestudies/Gohmann%20Case%20Study.pdf.

Case Study: University of Arkansas Harmon Avenue Parking Facility, *Engius Construction Intelligence Case Studies*, Stillwater, Okla., n.d. [Online]. Available: http://www.engius.com/publications/casestudies/Case%20Study%20-%20University%20of%20Arkansas%20Parking.pdf.

Case Study: University of Oklahoma Memorial Stadium, Norman, Oklahoma, *Engius Construction Intelligence Case Studies*, Stillwater, Okla., n.d. [Online]. Available: http://www.engius.com/publications/casestudies/Flintco%20OU%20Stadium%20Construction.pdf.

Case Study: Washington Metropolitan Area Transit Authority, Washington D.C., *Engius Construction Intelligence Case Studies*, Stillwater, Okla., n.d. [Online]. Available: http://www.engius.com/publications/casestudies/WMATA%20Case%20Study.pdf.

Castro, S. and N. Dawood, "RoadSim: Simulation Modelling and Visualisation in Road Construction," Presented at CONVR2004: Conference on Construction Applications of Virtual Reality, Lisbon, Portugal, Sep. 14–15, 2004.

Road construction is an equipment-intensive process, and its planning and performance management are essentially different from the methods usually adopted for other construction activities.

This is the result of (1) the high value of the road contracts, (2) the high cost of the inputs (equipment and materials), (3) the physical extension of the works, (4) the sensitivity of the works to the meteorological factors, (5) the environmental impacts, and (6) the potential conflicts with other social and economic activities. Current practices in the industry suggested that road construction planning is inefficient and projects are often over budget and time. The main reason is that project managers only use their experiences, historical company data, and gut feeling to elaborate mental models to deal with uncertainty and manage the planning and construction processes. However, the stochastic nature of a certain number of events, the rules governing the intervention of each resource, and respective interactions associated with space constrains cannot be dealt with efficiently using traditional planning methods. Efficiency gains can only be obtained with the introduction of new and more innovative tools to assist managers in planning and managing road construction projects to construct projects on time and on budget. The tools should be able to assist managers to study and compare all possible strategies and methodologies for the execution of the works and ensure that the planner's choice corresponds with the most advantageous possibility. To overcome the limitation faced by traditional planning tools and automate the road construction planning process, a computer-based system has been developed, incorporating a knowledge base, a simulation of the principal road construction operations, and the visualization of the result and impacts of the construction activity. The system is designated RoadSim and the respective framework is described in this paper.

Chin, S., S. Yoon, Y.-S. Kim, J. Ryu, C. Choi, and C.-Y. Cho, "Realtime 4D CAD = RFID for Project Progress Management," Presented at the Construction Research Congress 2005: Broadening Perspectives, San Diego, Calif., 2005.

The conference sub-title "Broadening Perspectives" amplifies the need for us all to learn from the past and to look into new challenges and opportunities available today and in the future. The conference provides a stimulating venue for discussion and intellectual argument that may result from conflicting interpretations and divergent thinking. These are essential to advancing research and understanding. Topics covered are: Lean Construction, Housing, Sustainability, Construction Automation and Robotics, Education and Workforce, Supply Chain Management, Productivity and Methods, Project and Risk Management, Contracts and Organizations, Infrastructure, and Information Technology.

Collins, J., "Case Builds for RFID in Construction," *RFID Journal*, 2004.

Fluor Construction found that active RFID tags could track large metal pipes stacked on a truck with 100% accuracy. However, there are issues to overcome before the technology is widely used in the construction industry. In September 2003, an RFID trial was conducted at a pipe fabrication plant in Houston, Texas, to determine whether RFID could help automate the shipment and delivery of key materials from fabrication plants to construction sites. One key goal was to see if the technology could withstand the rigors of harsh construction industry environments.

Compare Data Collection Terminals, 2005.

Handheld barcode scanners equipped portable data terminals and data collectors. Batch or Wireless (802.11b) Palm OS and Windows PocketPC Handheld PDA with barcode scanning capabilities.

Corley, G.R., G.H. Bunch, and C. Piper, "A Study of Webcamera Types and Costs," *ASC Proceedings of the 41st Annual Conference*, Cincinnati, Ohio, Apr. 6–9, 2005.

The use of webcams (video cameras specially designed to capture and transmit video and images over the Internet) is growing, as evidenced by the influx of webcams and after-market accessories in recent years. The evolution of the technology and the surge in development has attracted a host of new webcam manufacturers, vendors, and specialty contractors. This paper presents an investigation of webcams and their use in the construction industry. A literature review, an Internet search, and personal interviews were conducted to evaluate the use of webcams and to collect data about the types, features, and estimated costs.

Couture, J., "PDA Application Development at the Department of Transportation," *Maine IS Technology* (2), 2004 [Online]. Available: http://www.maine.gov/newsletter/feb2004/pda_application_development_at_t.htm.

The purpose of the environmental application was to facilitate the collection of data at properties along a construction site where well water samples are collected and taken to a lab for testing. Sample results were sent back from the lab to the Maine DOT and entered into the Ground Water and Hazardous Waste Office's database. Their specifications for this project also included the desire to collect GPS data and a digital image to better pinpoint each well's location for future reference.

Crews, T., "A Guide to Understanding and Interpreting Rugged Computer Specs," *PenComputing*, 2004 [Online]. Available: http://www.pencomputing.com/frames/textblock_rugged_machine.html.

Crews, T., "Rugged Specs Primer," *PenComputing*, 2004 [Online]. Available: http://www.pencomputing.com/frames/rugged_machine.html.

Crews, T., "Definitions and Specifications: NEMA Ratings," *Rugged PC Review*, 2006 [Online]. Available: http://www.ruggedpcreview.com/3_definitions_nema.html.

National Electrical Manufacturer's Association (NEMA) ratings are rarely applied to mobile devices, and are mainly applied to fixed enclosures. For example, a NEMA rating would be applied to a fixed electrical box mounted outside or to a fixed enclosure used to house a wireless access point. Most enclosures rated for use in an outside environment include a NEMA 4 rating. NEMA ratings have more stringent testing requirements to verify protection from external ice, corrosive materials, oil immersion, dust, water, etc. These stringent testing requirements can rarely be applied to mobile devices, but there is a correlation between NEMA ratings and IP ratings. However, this correlation is limited to dust and water. Please note that although it is possible to compare NEMA ratings and IP ratings, any such comparison is only related to the protection provided against dust and moisture. A few manufacturers of mobile computers will include NEMA ratings in their specifications, and it is important to understand how the NEMA specification correlates to a product's IP rating.

Crews, T.A., "Understanding Ruggedized Mobile Computer Specifications," *DBM Specialist Degree Paper*, 2004 [Online]. Available: http://www.dcenter.com/About/SDBM/Crews.pdf.

As demand for ruggedized mobile computers continues to grow, so does the number of different products offered to the market. This has led to a large number of devices that claim industrial ruggedization; however, in many circumstances these devices are simply enhanced commercial designs that include limited benefits. Many of these devices are manufactured for use in very specific environments.

Czerniak, R.J., *NCHRP Synthesis of Highway Practice 301*, *Collecting, Processing, and Integrating GPS Data into GIS*, Transportation Research Board, National Research Council, Washington, D.C., 2002, 65 pp.

This synthesis report will be of interest to various transportation-related groups around the world involved in collecting positional data with GPS and integrating these data into existing GIS. The focus is on the major issues that these groups are facing with data collection, data smoothing, and data integration, including identification of inaccurate, bad, or missing data points, and the lack of standard map matching algorithms. It notes that each application uses its own GPS equipment, GIS database, and internal set of GPS data processing rules, and that information sharing and coordination has been limited.

Dawood, N., E. Sriprasert, Z. Mallasi, and B. Hobbs, "Development of an Integrated Information Resource Base for 4D/VR Construction Process Simulation," Presented at AVR II and CONVR, Chalmers, Gothenburg, Sweden, Oct. 4–5, 2001.

This paper reports on the development of an integrated database to act as an information resource base for 4D/VR (virtual reality) construction process simulation. A comprehensive database was designed, implemented, and populated with the School of Health Construction Project (a six million pound, three-story development at the University of Teesside campus) as part of VIRCON. The database is composed of a core database of building components that is in turn integrated with a CAD package (AUTOCAD 2000), a Project Management Package (MS Project), and Graphical User Interfaces.

Dawood, N., E. Sriprasert, Z. Mallasi, and B. Hobbs, "4D Visualisation Development: Real Life Case Studies," *Conference Proceedings—Distributing Knowledge in Building*, 2002 [Online]. Available: http://itc.scix.net/data/works/att/w78-2002-87content.pdf.

Visual 4D planning and scheduling technique that combines 3D CAD models with construction activities (time) has proven benefits over traditional tools, such as bar charts and network diagrams. In 4D models, project participants can effectively visualize and analyze problems regarding sequential, spatial, and temporal aspects of construction schedules. As a consequence, users can generate more robust schedules and hence reduce reworks and improve productivity. Currently, there are several working research prototypes and commercial software that have the ability to generate a 4D model. However, two major issues arise regarding the current 4D development approaches and the use of commercial software. These are the limited feasibility to large and complex projects, and inflexibility to incorporate more construction problems (nD modeling), especially for process constraints such as spatial conflicts and the availability of information and resources.

DeBrunner, J. and A. Lytle, *Intelligent and Automated Construction Job Site Breakout,* FIATECH, University of Texas at Austin, 2005.

Lasar scanning presentation slides.

DeFinis, A., "New Maturity Monitoring System Produces All the Data DOT Needs," *Roads and Bridges*, Mar. 2005, pp. 38–39.

The Michigan DOT has tested a device to be used as a concrete maturity monitoring system (CMMS). The Michigan DOT used a RFID that contained information on tag id, location, logging interval, pour time, date, sample count, average temperature, high and low temperature, time temperature factor, and strength. A portable device read information from the RFID tags through up to 8 in. of concrete and the data obtained were used to determine the strength of the concrete on the road. The project was a success, as all 19 of the tags in the road worked, and construction impact on nearby businesses was minimized.

DeFinis, A.J., *Concrete Maturity Testing in Michigan*, 2004.

In the near future the Michigan DOT would like to develop a special provision that would allow contractors in the state to use concrete maturity testing to estimate the strength development of concrete pavements. To develop a specification, the Michigan DOT was looking for a contractor and a suitable project to test the use of a possible wireless concrete maturity monitoring system (CMMS). The Michigan DOT has experimented itself with the use of a CMMS on a couple of select projects around the state. The CMMS was not used as a full-scale testing system on any of their selected projects. The report includes cost information.

de Vries, B. and J. Harink, "Construction Analysis During the Design Process," Presented at the 11th International CAAD Futures Conference, Vienna, Austria, June 20–22, 2005.

4D CAD systems are used by contractors for visually checking the construction process. To enable simulation of the construction process, the construction planner links building components from a CAD model with the activities from a project planning. In this paper, a method to generate a project planning directly from a CAD model using basic construction knowledge is described. A case study is discussed briefly to show the current results and the shortcomings. Finally, an outlook is presented on a more advanced implementation that is (also) useful for designers.

Dias, J. Miguel Salles, A.J. Capo, J. Carreras, R. Galli, and M. Gamito, "A4D: Augmented Reality 4D System for Architecture and Building Construction," Presented at CONVR, Virginia Polytechnic University, Blacksburg, Sep. 24–26, 2003.

A4D is a cooperative design system for AEC that integrates state-of-art technologies in the area of 3D computer graphics, computer vision, augmented reality, 4D simulation, human–computer interaction, computer-supported cooperative work, mobile computing, and sensory devices. A4D's objective is to help the AEC sectors to build more efficiently; accurately; with lower costs; in a manner that is more planned, safer, easier and humanized for all, by developing and introducing new augmented reality technologies and novel workplace design concepts in AEC. A4D supports the reality–virtuality continuum in AEC, by enhancing the real environment with fixed and mobile augmented reality, supported in wearable system elements, vision-based user and object tracking systems (currently for in-door usage), and multi-user virtual environment. A4D also integrates building construction project scheduling technology and supports interactive 4D (3D+time) visualization and design. A4D developments aim and tackle high innovative research; however, its concepts do not disregard relevant issues such as applicability, human-factors, and prospects on cost- and time-effectiveness improvements.

Dickens, N., "Virtual Reality in Construction Education and Industry," In *Associated Builders and Contractors Trimmer Education Foundation Winner in 2006 Student Essay Contest*, The University of Southern Mississippi, Hattiesburg, 2006.

Presently, the construction industry uses physical models and/or physical mock-ups to describe a proposed structure to be built. However, this approach is costly, time consuming, and the physical models created cannot be easily changed. This essay will illustrate the possible advantages of using VR environments in construction to improve education and training as well as the erection process of complex projects. It is based on current literature that highlight actual uses of VR environments in construction and also describes possible future utilizations of VR.

Doherty, P., "The Third Wave: The Building as Computer," *DesignIntelligence*, Vol. 8, No. 1, 2002.

The built environment is entering a wave that will change how buildings are perceived forever. The emergence of telecommunications and IT as a Fourth Utility in buildings has created the opportunity for facilities to become interactive, computing environments, placing a higher asset value on a building as pervasive computing allows the building to interact with its inhabitants.

Domich, P. and I. Friedland, *Innovation in Vertical and Horizontal Construction: Lessons for the Transportation Industry*, Federal Highway Administration, Washington, D.C., 2005.

With its strong ties to the vertical (low- and high-rise building) construction industries, the Civil Engineering Research Foundation (CERF) was able to open the doors and help FHWA examine how innovation occurs within the vertical construction industry. In addition, some very important and interesting innovative approaches that the vertical construction industry uses to finance, manage, and deliver construction projects were gathered. Some of these ideas may be difficult to implement in public-sector construction; others may have direct applicability today. All of the ideas discussed in this report, however, have had a positive impact on the vertical construction world and are worth additional discussion and possible adoption as we try to innovate for the future in our delivery of a national surface transportation program to better serve the mobility needs of the nation.

Dowd, B., "AASHTO's SiteManager Tames Contract Documentation," *Public Roads*, Vol. 6, 1998 [Online]. Available: http://www.tfhrc.gov/pubrds/may98/aashto.htm.

By automating and improving contract recordkeeping, SiteManager helps state highway agencies spend less time on paperwork, which means lower costs. States that have already implemented similar automated contract management systems predict that the systems will save them several million dollars each year, according to MCI Systemhouse, which developed SiteManager under contract to AASHTO.

Emerging Construction Technologies: 3D GPS Based Earthmoving, *Construction Engineering & Management* (*CEM*), Purdue University, West Lafayette, Ind., 2002 [Online]. Available: http://www.new-technologies.org/ECT/Other/gps.htm.

Construction design includes using a construction planning or survey software to create an elevation design to which the machine operators should work. This design may be a simple production dozing such as a dual-sloped plan for field drainage or a much more complex design, showing elements such as super-elevated curves.

Emerging Technology for Design and Construction Committee, Technical Activities Division, Transportation Research Board, National Research Council, Washington, 2005.

An important function of TRB is to stimulate research that addresses problems facing the transportation community. In support of this function, TRB technical committees identify problems, and develop and disseminate research problem statements for use by practitioners, researchers, and others.

"Environmental Spatial Information for Transportation: A Peer Exchange for Partnerships," Woods Hole, Mass., June 23–24, 2003.

This workshop, sponsored by the Office of National Environmental Policy Act Facilitation of the FHWA, was intended to share information and document lessons learned by early adopters of innovative environmental data-sharing practices. Participants came from a range of organizations, including state departments of transportation (DOTs), metropolitan planning organizations (MPOs), nonprofit organizations, and natural resources and regulatory agencies.

Fallon, K.K., *Best Practices in Information Technology Among A/E/C Firms*, 2000, presentation slides [Online]. Available: http://www.nwccc.org/presents/bestprac.ppt.

Identification of "Best Practices" and performance measurement related to construction project delivery.

Field Management TAG Meeting Minutes, *Meeting Minutes November 5, 2002, Austin, Texas*, 2002 [Online]. Available: www.tug.cloverleaf.net/2005TUG/TAG%20Meetings/2005FieldMgmtTAG.pdf.

Mission Statement: To support and enhance AASHTO's Trns.port FieldManager suite of software by advising the Trns.port Users Group (TUG) and the Trns.port Task Force on decisions relating to direction, support, and services required for effective management of construction projects in the field.

Fischer, M., 4D CAD: Learning from Your Virtual Mistakes, presentation slides, Northwest Construction Consumer Council (NWCCC), Seattle, Wash., 1999 [Online]. Available: http://www.nwccc.org/presents/fischer1.pdf.

4D CAD combines a 3D CAD model with the construction schedule to simulate and display the construction sequence of a project with the computer. First developed about 10 years ago, 4D CAD is now increasingly used to communicate construction schedules more effectively to all project stakeholders and to try out alternative designs and construction approaches before actual construction.

Fischer, M. and R. Akbas, *Automated Detection and Updating of Construction Activity Progress from Time-Lapse Images*, Center for Integrated Facility Engineering (CIFE) Seed Proposal—PMT0301 slide presentation, 2003.

A low-cost progress data collection technique is proposed for construction sites using time-lapse video. We build on our existing research on 4D CAD and geometric, parameter-based 4D models and apply computer vision techniques to webcam images of construction sites to provide frequent, rapid, and automated feedback on the performance of construction crews with respect to the project schedule. The main steps for this research are camera configuration, camera calibration, segmentation of the images, and tracking of the crews and progress of work on components or in areas. As a result of this research, automatic, accurate, and more frequent progress data collection and updating of the schedule and 4D model will be possible.

Fischer, M. and C. Kam, *PM4D Final Report, CIFE Technical Report No. 143*, Department of Civil and Environmental Engineering and Center for Integrated Engineering, Stanford University, Stanford, Calif., 2002.

This Product Model and Fourth Dimension (PM4D) report presents the findings from the design and construction of the Helsinki University of Technology Auditorium Hall 600 (HUT-600) in Finland. Running simultaneously with the design and construction of the HUT-600 project, an international research partnership extensively applied the product modeling approach; tested the Industry Foundation Classes interoperability standards; and employed an array of design, visualization, simulation, and analysis tools on the 17-month, USD $5 million capital project. Through our dissemination of project experiences and analytical results, it is hoped that building owners, end users, and project teams will take advantage of the current capabilities and benefits of the PM4D approach, which leverages commercially available state-of-the-art analytical and visualization tools to optimize the design, construction, and operation of a proposed facility during early project phases.

Fischer, M. and J. Kunz, *The Scope and Role of Information Technology in Construction, CIFE Technical Report No. 156*, Center for Integrated Engineering, Stanford University, Stanford, Calif., 2004.

Since 1988, personnel at CIFE at Stanford University have been working on methods and approaches to integrate project information and leverage information across disciplines and phases to create efficient work processes and enable better project decisions. There are certainly improvements necessary and possible in the software tools and underlying methods used by the individual disciplines today. However, the major opportunity for improving the design and construction of facilities lies at the interfaces between disciplines. Hence, this paper focuses on the role and scope of IT in support of multidisciplinary planning and coordination of construction projects. Finding a way to participate in such an integrated project design and construction process will be a key challenge and opportunity for individuals and firms in the foreseeable future.

Fischer, M. and K.M. Liston, *Wish List for 4D Environments: A WDI R&D Perspective*, Stanford University, Stanford, Calif., 2001.

This document outlines the functionality needed for a 4D environment to serve the needs of the Paperless Design Project at Walt Disney Imagineering (WDI). This report was originally written for Paperless Design Team members and Research and Development personnel at WDI to understand our "wish-list" of functionality needed to support 4D environments. This document has been edited to reflect a more general perspective. Ultimately, this document should serve as a roadmap for the development of next generation CAD, project management, and concurrent engineering tools. It is not envisioned that all the functionality discussed herein needs to be provided in one product, but any products used in this process should provide the "hooks" to enable the representation and linking of the information required for 4D modeling.

Foreman, C., "Grading Is Made Easier with GPS," *Construction Week*, May 28, 2005.

Many earthmoving contractors are finding success with the help of automated grade control technologies, which provide not only precise, accurate results, but also a productivity enhancing competitive edge. These days it is all about machine control, which extends from basic systems that rely on stringlines and lasers, to highly precise 3D GPS. Most of the systems are fitted into construction equipment as an after-market add-on, although some manufacturers are now offering integrated systems at the time of manufacture.

Friedland, I., “From Vertical to Horizontal: Learning from the Innovations of the Building Construction Industry,” *FOCUS: Accelerating Infrastructure Innovations*, Aug. 2005.

From New York’s John F. Kennedy (JFK) Airport to the Walt Disney Concert Hall in Los Angeles, observing and learning from the innovations of the vertical construction industry (i.e., buildings and related facilities) was the goal of a domestic technology scanning tour sponsored by the FHWA. Modeled on the international technology scanning program, jointly sponsored by AASHTO and FHWA, the scan was facilitated by the Civil Engineering Research Foundation. Scanning team members represented AASHTO, state transportation agencies, the National Association of County Engineers, industry, and FHWA.

Gagnon, J.J., “Monitoring Corps Projects with Web Cameras,” In *Ice Engineering Information Exchange Bulletin,* U.S. Army Engineer Research and Development Center, Vicksburg, Miss., 2002.

Many U.S. Army Corps of Engineers projects need monitoring and inspection at regular intervals, if not continuously, to track progress, assess evolving conditions, or anticipate undesirable events. Examples of possible uses include observation of riverbank erosion, construction sites, demonstration sites, and machine operation, as well as hydro-meteorological documentation of field sites, monitoring of endangered species, and—especially now—increased security. Physical monitoring can drain personnel and equipment resources, especially if the site is remote, and important events may be missed because of unfortunate timing. Photographs documenting site conditions are often requested by more than one person or agency. In some instances, a remote camera image may be preferred over a personal site visit; for example, when monitoring endangered species. The Internet provides a convenient way to access images from Web cameras.

Gao, J., M. Fischer, T. Tollefsen, and T. Haugen, “Experiences with 3D and 4D CAD on Building Construction Projects: Benefits for Project Success and Controllable Implementation Factors,” *Construction Informatics Digital Library*, 2005 [Online]. Available: http://itc.scix.net/cgi-bin/works/Show?_id=w78%2d2005%2dd3%2d1%2dgao&sort=DEFAULT&search=4D%20Cad&hits=158.

From our experience reviewing a wide range of questions that AEC professionals are asking, the AEC industry is facing the challenge to determine the benefits of 3D and 4D CAD and what it takes to implement this advanced technology. This paper focuses on past experiences of using 3D and 4D CAD on building construction projects. By reviewing a collection of AEC projects from the United States, Norway, and elsewhere, the authors demonstrate that: (1) 3D CAD allows improved design, team collaboration, and smooth project execution; and (2) 4D CAD enables the exploration and improvement of the project execution strategy, facilitates improvements in constructability with corresponding gains in on-site productivity, and makes possible the rapid identification and resolution of time–space conflicts. These experiences acknowledge 3D and 4D CAD as a key driver and a primary enabler for better design of product, more cohesive organization, and more efficient process that lead to project success. This paper also illustrates the real implications of working with 3D and 4D CAD. A detailed case study on the Pilestredet Park Project in Oslo, Norway, demonstrates that: 3D and 4D CAD is not simply a question of investment but depends more on appropriate planning and managing the implementation; that is, understanding what you can and want to do; identifying right timing, people, data, and tools; and putting 3D and 4D models in the right process to reap the benefits. This outcome will enable facility managers and AEC service providers to make informed judgments about the appropriate controllable factors in implementing 3D and 4D CAD.

The Gift of James Smithson, FIATECH, University of Texas at Austin, presentation slides, n.d.

FIATECH Powerpoint slide presentation of Engineering Document Management System using A/E/C CADD Standards on Smithsonian Institution building project.

Gilbert, A., “RFID Deadline Hits Defense Industry,” CNET Networks, Inc., 2005 [Online]. Available: http://news.com.com/RFID+deadline+hits+defense+industry/2100-1012_3-5947661.html.

Global Positioning System (*GPS*) *Surveying*, Report FHWA-HRT-04-071, Federal Highway Administration, Washington, D.C., n.d.

Goodrum, P.M., J. Dai, C.R. Wood, and M. King, “The Use of the Concrete Maturity Method in the Construction of Industrial Facilities: A Case Study,” FIATECH, University of Texas at Austin, 2004.

The pilot project described in this report was a field trial of recent technology that predicts in situ strength of concrete using the concrete maturity method. The pilot was conducted in realistic field conditions by Flour Corp. personnel over 2 months during the main concrete placement phases of the Amgen Opus Program Project in Puerto Rico. This report reviews the concrete maturity method, and describes the technology and field experience in trials of that technology.

Gopinath, R. and J.I. Messner, “Applying Immersive Virtual Facility Prototyping in the AEC Industry,” Presented at CONVR2004: Conference on Construction Applications of Virtual Reality, Lisbon, Portugal, Sep. 14–15, 2004.

The design and construction of facilities requires the conceptualization of complex systems and processes. Although many industries have embraced rapid prototyping processes and technologies, the use of prototypes in the building industry remains in its infancy. Expensive physical prototypes including scale models and mock-ups of building components are used to analyze design and construction; however, they represent only a single snapshot or configuration of the construction process. 3D and 4D CAD tools allow virtual models to be constructed; however, they are typically challenging to manipulate and limited by small-scale display for individual users. There is a need to develop better methods to visualize and manipulate virtual models of facility products and construction processes within the AEC industry. Digital technologies and media are altering the prototyping tools available to facility designers and contractors. This paper presents a brief background of prototyping techniques and discusses the concept of Immersive Virtual Facility Prototyping (IVFP) that can provide a foundation for the widespread use of virtual full-scale prototyping in the AEC industry. The IVFP is developed from the display of a facility model in an immersive virtual environment. The process of developing the IVFP must focus on both the model and the media of display. A case study illustrating the value of implementing an IVFP on a building construction project is presented. This case study shows that IVFPs can improve the communication of design and construction information to the team members. It also illustrates several challenges related to implementing IVFPs on large-scale building projects including the acceptance of the technology by the project team, model development challenges, and the development of relatively low-cost display systems for viewing virtual prototypes at full scale. Overall, the implementation of the IVFP shows clear promise to support significant improvements in the methods used to prototype building projects.

GPS/GIS Inspection and Analysis Tools for Highway Construction [Detailed web page view of project progress]. Transportation Research Board, National Research Council, Washington, D.C., n.d. [Online]. Available: http://rip.trb.org/browse/dproject.asp?n=10158 [accessed Nov. 26, 2005].

Florida DOT research project description of GPS/GIS inspection and analysis tools for highway construction, BD543-08.

GPS/GIS Inspection and Analysis Tools for highway construction: GPS Data Interface with SiteManager, Florida DOT, Tallahassee, 2005, presentation slides.

Powerpoint slideshow with screenshot images of SiteManager software application for personal digital assistant (PDA) and desktop.

GPS Integration in Highway Design and Construction: Quality Improvement Opportunities in the Public Sector, McAninch Corporation, West Des Moines, Iowa, 2005.

GPS Utilization Report, *2003 AASHTO Survey of DOT GPS Usage*, AASHTO Technology Implementation Group, Washington, D.C., 2003–2005.

Guan, L., *Sensor-Based Robot Navigation and Map Construction*, University of North Carolina, Chapel Hill, 2006 [Online]. Available: http://www.cs.unc.edu/~lguan/COMP290-58.files/Final Report.htm [accessed May 25, 2006].

A general program framework for the ER1 robot, which consists of a sensing, control, and motion planning module is presented. Based on the platform, a specific application—a topological map building of the third floor of Sitterson Hall based on one laptop, one webcam, and one ER1 robot—is proposed. Different algorithms are introduced to achieve robust navigation. Although a real topological map was not completed with the time provided because of the instability of landmark recognition, experiments on simulated data show the feasibility of map construction. Given the robustness of the navigation algorithm, it is expected that the final goal will be achieved shortly.

Haas, C., R. Griffin, R. Navon, A. Brecher, D. Livingston, and D. Bullock, "Emerging Technologies for Transportation Construction," In *Transportation in the New Millennium: State of the Art and Future Directions, Perspectives from Transportation Research Board Standing Committees*, Transportation Research Board, National Research Council, Washington, D.C., 2000.

In the next millennium, light rail transit and other urban transit systems will be greatly expanded; however, highways will continue to play a major role in transportation. With the anticipated increasing demand placed on roads, taking even a single lane out of the transportation network temporarily for repair or reconstruction will be highly disruptive. As a result, construction crews will have to perform their work more rapidly. Indeed, contracting incentives for doing so already exist. In addition, design, materials, and workmanship will have to provide a long-lasting product to avoid the need for further traffic disruptions for repair or reconstruction. As the new century approaches and the baby boomers age and begin to retire, labor shortages are anticipated. Therefore, new construction automation, equipment, and techniques will be needed so that the equivalent work can be performed with fewer workers. The automation is likely to prove more reliable, efficient, and cost-effective as well.

Haas, C.T., R.L. Tucker, K.S. Saidi, and N.A. Balli, *The Value of Handheld Computers in Construction*, University of Texas, Austin, 2002.

HHCs have the potential to solve some of these problems by providing field workers with accurate, reliable, and timely information at the location where it is needed. In addition, HHCs could enable workers to transmit up-to-date project information back to management directly from the construction site, when coupled with the implementation of CCIS's Tier II strategy. Thus, HHCs can increase the amount of direct work on a project indirectly by directly decreasing the time spent on support work (such as accessing drawings and sending RFIs) and by reducing idle time.

Hall, J.P., Ed., *Transportation Research Circular E-C046: Using Spatial Data, Tools, and Technologies to Improve Program Delivery*, Transportation Research Board, National Research Council, Washington, D.C., 2002.

New spatial data, tools, and technologies are enhancing and streamlining transportation program delivery activities in many parts of the country. The TRB Committee on Statewide Data and Information Systems hosted a peer exchange to identify the kinds of spatial data tools and information that are most effective in delivering multimodal transportation programs. The optimum use of these tools in identifying and prioritizing programs and in improving program delivery was also explored. Results of the exchange provided findings and insights into what kinds of spatial data, information, tools, and technologies can yield the most value and benefit in improving transportation planning and program delivery processes for transportation agencies.

Hammad, A., C. Zhang, Y. Hu, and E. Mozaffari, "Mobile Model-Based Bridge Lifecycle Management Systems," Presented at CONVR2004: Conference on Construction Applications of Virtual Reality, Lisbon, Portugal, Sep. 14–15, 2004.

This paper discusses the requirements for developing mobile model-based bridge lifecycle management systems (MMBLMSs). These new systems should link all the information about the life-cycle stages of a bridge (e.g., construction, inspection, and maintenance) to a 4D model of the bridge incorporating different scales of space and time to record events throughout the life-cycle with suitable levels of details. In addition, MMBLMSs should support distributed databases and mobile location-based computing by providing user interfaces that could be used on thin clients, such as PDAs and tablet PCs, equipped with wireless communications and tracking devices, such as GPS receivers. A prototype system developed in Java language is used to demonstrate the feasibility of the proposed methodology for realizing these systems.

Hampton, T., "3D Grade Control Puts Designers Right in the Operator's Seat," *Engineering News-Record*, Oct. 3, 2005.

GPS, which guides automatic grade controls on earthmoving machines, is well on its way to becoming an industry standard for survey, design, and construction. However, there are many obstacles to clear before that happens. Automation is closing the precipitous gap between the drawing board and the field. It is changing the way engineers design infrastructure, just as much as it is changing the way operators drive dozers.

Hampton, T., "'Smart' Jobsites are Coming," *Engineering News-Record*, 2005 [Online]. Available: http://enr.ecnext.com/free-scripts/comsite2.pl?page=enr_document&article=preqar051027.

Like the border of a giant jigsaw puzzle, GPS are starting to bring together electronic management tools. The complete picture won't be clear though until all the pieces fit. Engineers can expect the puzzle to remain for a few more years, perhaps decades, as the industry works out the kinks. For one, construction moves at a snail's pace, technologically speaking. Firms have been slow to incorporate GPS into survey, design, and project delivery because of its complexity.

Hampton, T., "Award of Excellence Winner 2005: Dwayne McAninch," *Engineering News-Record*, 2006 [Online]. Available: http://www.enr.ecnext.com/free-scripts/comsite2.pl?page=enr_document&article=people060410-1.

Since 1999, the man who steered the controls' early development has gambled millions of dollars on the once-unproven technology. Through word of mouth, he has educated owners, engineers, and contractors by producing videos, giving talks at conferences, and inviting competitors to Des Moines to see his machines work. He made the unusual decision to share performance data with the rest of the world. McAninch believed that open communication would help the industry warm up to digital grade controls.

Hannon, J.J., "Instructor Utilization of the Tablet PC in the Construction Classroom," Presented at the 41st Annual Conference of the Associated Schools of Construction, Cincinnati, Ohio, Apr. 6–9, 2005.

The author has experimented with a tablet PC and peer-to-peer projector networking in the delivery of undergraduate construction management courses. This paper presents the successes and drawbacks of the experience as well as information concerning the hardware and software involved for instructors contemplating such changes and/or solutions. The tablet PC provides advantages as well as disadvantages in relation to notebook computers in instructor delivery of undergraduate construction management curriculum. The availability of mobile projection systems allow the instructor to set up course delivery in any location capable of reflecting the projector's output. In addition, compact mobile computers and projectors give the instructor independence in an environment of scarce classroom resources. Reporting as a relative early adopter of these hardware and software combinations, other instructors can use the information to make more informed decisions on products that are quickly becoming smaller, more sophisticated, and lower in price.

Hannon, J.J., "Authentic Community Concept Applied to A/E/C," Presented at the 2006 AACE International Transactions, Las Vegas, Nev., 2006.

At the project level, project managers of AEC projects can use the concept of authentic community in two dimensions, also identified by Unger. First, project managers must effectively communicate with other business functions within their organization. To properly execute the duties of planning, monitoring, documenting, and administering for the project, communication and interaction of available internal resources is imperative. Second, project managers of AEC projects must also effectively communicate with stakeholders outside of their business organization. Communication with and coordination of vendors, suppliers, consultants, subcontractors, and other agents is equally critical.

Harder, B.T. and R. Benke, *NCHRP Synthesis of Highway Practice 355*: *Transportation Technology Transfer: Successes, Challenges, and Needs*, Transportation Research Board, National Research Council, Washington, D.C., 2005, 85 pp.

This synthesis presents information on the use of technology transfer practices in the highway transportation community. It is intended to assist transportation agencies and other transportation research organizations in expediting innovation to practice, thereby increasing safety, enhancing performance, and reducing costs. The report documents successful practices, discusses challenges encountered, and identifies the needs of those responsible for sponsoring, facilitating, and conducting technology transfer activities and processes. It incorporates practices within state departments of transportation and other programs such as Local and Tribal Assistance Programs' Technology Transfer Centers and the Resource Center and division offices of FHWA. Areas of interest include organizational structures, political and legal aspects affecting technology transfer, resources (financial, personnel, technology, facilities, and equipment), strategies and tools, and performance evaluation. Comparisons with practices from the private sector are included.

The HardTrack System Concrete Maturity Modeling, WAKE, Inc., Sturgis, Mich., original edition, marketing brochure, n.d.

The wireless HardTrack system uses buried RFID transponder tags to track the true temperatures of your poured concrete. Custom software loaded onto a handheld PC enables two-way radio frequency communication. Track data from multiple tags—and multiple projects—without wires.

Hartmann, T., M. Fischer, E. Rank, M. Schreyer, and F. Neuberg, "Integration of a Three-Dimensional CAD Environment into an Interactive Workspace," In *CIFE Technical Report No. 146*, Stanford University, Stanford, Calif., 2003.

In the design and construction process of a building the tasks to accomplish are distributed to many different participants. All of these participants use different kinds of software applications, which all use a different view of the overall project model. The project's participants discuss mutual interactions within their models in meetings to find the affects of their work on the work of others. For example, if the architect changes the geometry of parts of the project's building, this will have effects on the cost-estimation, as the quantities used in the estimation have changed. Owing to a lack of adequate interfaces between the different used applications, it is common practice within meetings to first explain and describe different circumstances. Afterward, all participants of the meeting will update their application models. Interactive workspaces integrate modern computer technologies to enable data exchange and control between applications. This exchange then will hopefully be supportive for describing and explaining different problems occurring within a project meeting by using the software applications with which the participants model their respective views of the building. CIFE is developing such an interactive workspace. A number of different applications used in civil engineering are already integrated. Nevertheless, it is not yet possible to work with a CAD environment commonly used by architects to model the geometrical aspects of the project model. This report describes the integration of such a CAD application within an interactive workspace.

Haymaker, J. and M. Fischer, *Challenges and Benefits of 4D Modeling on the Walt Disney Concert Hall Project: CIFE Working Paper No. 64*, Department of Civil and Environmental Engineering and Center for Integrated Engineering, Stanford University, Stanford, Calif., 2001.

The goal was to test the applicability and usefulness of 4D modeling and of the 4D prototype software developed between CIFE and Walt Disney Imagineering on a complex project like the Walt Disney Concert Hall in Los Angeles. The 4D models built with the assistance of CIFE helped the construction team find many schedule inconsistencies; resolve access, scaffolding, and hoisting issues for the exterior and interior construction in a timely manner; inform more stakeholders of the approach to construction and of the schedule; and engage subcontractors in the scheduling process.

Haymaker, J., B. Suter, J. Kunz, and M. Fischer, "PERSPECTORS: Automating the Construction and Coordination of Multidisciplinary 3D Design Representations," In *CIFE Technical Report No. 145*, Stanford University, Stanford, Calif., 2003.

A multidisciplinary project model was formalized as a directed acyclic graph of dependencies between representations. For the nodes of this graph, a generic representation, called a "perspective," was formalized that contains "features" that describe the design for a specific task. These features contain data types such as 3D surfaces, lines, and points, as well as relationships to other features. For the arcs of this graph, a generic reasoning mechanism called a "perspector" is formalized, which analyzes any number of "source perspectives" to produce one "dependent perspective." Engineers from different disciplines use perspectors to transform source perspectives into dependent perspectives that are useful for their tasks. Dependent perspectives serve as source perspectives for other dependent perspectives, leading to a self-organizing graph of dependencies between perspectives. This approach with two multidisciplinary engineering problems from the Walt Disney Concert Hall is described. Perspectors and perspectives enable engineers to use design representations that share a common theoretical foundation. They allow engineers to automatically generate task-specific representations from representations produced by other engineers.

Heesom, D. and L. Mahdjoubi, "Trends of 4D CAD Applications for Construction Planning," *Construction Management and Economics*, Vol. 22, No. 2, 2004, pp. 171–182.

Since the early 1990s, there has been a growing interest in 4D CAD for construction project planning. Commercial 4D CAD applications are becoming more accessible and the use of this technology allows the construction planner to produce more rigorous schedules. A review of the technical competencies of these packages highlights that most of the commercially available packages concentrate on the use of 4D CAD simulations for aesthetic visualization purposes. Very few packages offer the ability to carry out analytical tasks on the developed simulation and this is often left to the interpretation of the user. A thorough appraisal of emerging research developments in 4D planning highlights that this technology is employed for various applications; however, the amount of detail required in a 4D simulation is still ambiguous. A model is proposed to determine the attributes required for use with each of the various applications of 4D CAD simulations. Finally, various lines of future research are highlighted, including the need for improved use of data exchange standards and the automation of linking the construction tasks to the 3D CAD model.

Hohner, L.N., "Working with a Super Model," *SitePrep Magazine*, Winter 2006, pp. 6–8.

Many data modeling service companies are beyond busy. To what do they attribute their excessive activity? Today's booming land development market is one factor in the growing demand for data modeling services. Its providers produce digital elevation models—also known as digital terrain models—the designs that reflect the existing and proposed workspace and are followed by the heavy equipment operator inside the cab using the latest in 3D technology. The limited number of experienced and knowledgeable providers in this market also contributes to overbooked schedules. "Few people out there in this business really know how to build a correct and accurate site model," says Dave Zimmerman, CEO of the Cosmopolis, Washington-based Earthwork Services (www.EarthworkServices.com). "The GPS model industry is like cars without gas . . . [there is] lots of hardware for sale out there and lots of people selling models but few who really do it right. A contractor finds out real fast if a model is bad, so a good or bad reputation spreads very fast."

Issa, R.R.A., "Virtual Reality: A Solution to Seamless Technology Integration in the AEC Industry?" In *Defining a Research Agenda for AEC Process/Product Development in 2000 and Beyond*, Berkeley–Stanford CE&M Workshop, Aug. 26–28, 1999, Stanford, Calif., 2000.

For VR applications to be successfully implemented in a complex industry such as construction, they must be part of a vertically integrated construction environment. Whether immersive or non-immersive techniques are used in the VR applications, users must be able to visualize design and construction information in 3D, photorealistic, and interactive images. The user must also be able to interact with external applications at real-time, thus allowing VR systems not only to be used as presentation tools, but also as a universal interface for all construction applications. Finally, construction professionals must be able to view, alter, test, etc., any function or part of the proposed design and at any stage of the project life cycle through the virtual space. Because of the magnitude and complexity of the construction projects, the traditional way of doing business in the construction industry is to divide the whole project into work packages according to well-established specialization. The work packages are assigned to specialty designers and contractors, respectively. Although a system such as this brings significant benefits to the industry, it also results in difficulties in communication and extensive collaboration among the participants of the project.

Issa, R.R.A., D. Fukai, and G. Lauderdale, "A Study of 3D and 2D Construction Drawings Acceptance in the Field," Presented at CONVR 2003, Sep. 24–26, 2003, Virginia Polytechnic Institute and State University, Blacksburg.

Advancements in computer and solid modeling technology have provided affordable and powerful tools for creating virtual models of buildings and structures. In spite of this growing technology, construction documentation largely remains in 2D format. The virtual model is discarded after the schematic design phase of the project and the inherent value of the model, its communication of the design intent, is not relayed to the construction management team. In essence, the construction team in the field must visualize the design intent from the 2D construction documents and specifications, a process done at best with varying levels of competency among individuals. This study focuses on the adaptation of 3D drawings in lieu of traditional 2D plans, elevations, and sections to perform construction tasks such as building layout, material fabrication, and assemblies. The results of the survey show that, depending on their educational background and the type of construction application and its complexity, the respondents considered 3D drawings easier to understand than 2D drawings.

Jacobson, D. and K.B. Kruse, *Leveraging Technology Investments Integration of GPS, GIS, and Maintenance Management*, Upper Great Plains Transportation Institute, North Dakota State University, Fargo, 2003.

This research project attempts to ease the data collection burden of the North Dakota DOT maintenance manager, while increasing and improving pavement condition information. The pilot project used HHC and GPS technology to capture pavement condition and location data. These data collection efforts were designed to be assimilated into current roadway management operations. This technology potentially can reduce field work of the maintenance manager.

Jennings, K.D., "Webcams for Contractors," *Construction Executive*, June 2003 [Online]. Available: http://oxblue.com/resource/pdf/ConstExecArticle.pdf.

Webcam technology is making inroads into the construction industry as a tool to help manage and archive projects. Webcams have been used in recent years for several reasons, primarily as a way to promote high-profile construction projects and improve remote surveillance. However, for some construction companies the technology has also become a vital project management tool. Although webcam images of construction projects are a great tool, they are only valuable if someone reviews and records the photographs, along with the project's progress. Many aspects of project management can use webcams, but administration and maintenance for the surveillance systems often can be a full-time job in itself.

Johnston, B., R. Wakefield, and M. O'Brien, "Exploring a Virtual Modeling Hierarchy for Construction: Two Case Studies," Presented at CONVR2004: Conference on Construction Applications of Virtual Reality, Lisbon, Portugal, Sep. 14–15, 2004.

The conversion of actual construction events into virtual representation is a challenging task. Applying virtual modeling and simulation as an analytic and predictive tool for construction planning is an even greater challenge. This paper explores some of the difficulties faced and suggests a modeling hierarchy developed with virtual programming experience gained from two construction assembly case studies.

Kamat, V.R. and J.C. Martinez, "Comparison of Simulation-Driven Construction Operations Visualization and 4D CAD," *Proceedings of the 2002 Winter Simulation Conference Construction Engineering and Management Program*, Virginia Polytechnic Institute and State University, Blacksburg, 2002.

Several recent research efforts in visualizing construction are rooted in scheduling. They involve linking activity-based construction schedules and 3D CAD models of facilities to describe discretely evolving construction "product" visualizations called 4D CAD. The focus is on communicating what component(s) is built where and when. The construction processes or operations actually involved in building them are usually implied. Ongoing research at Virginia Tech focuses on designing automated, simulation-driven methods to visualize, in addition to evolving construction products, the operations and processes that are performed in building them. In addition to what is built where and when, the effort is concerned with visualizing who builds it and how by depicting the interaction between involved machines, resources, and materials. This paper expounds the differences in concept, form, and content between 4D CAD and dynamic 3D visualization of operations simulations. An example of a structural steel framing operation is presented to elucidate the comparison.

Kim, H., H. Soleymani, S.H.B. Zadeh, S. Hounsell, M. King, and C.R. Wood, "Field Study of Concrete Maturity Method in Very Cold Weather," In *Smart Chips Project*, FIATECH, University of Texas at Austin, 2005.

The study described in this report assesses the reliability and potential benefit of using the concrete maturity method in very cold weather. Cold weather presents particular challenges for concrete construction including: (1) assuring that fresh concrete is not damaged by the cold, (2) that the concrete reaches appropriate strength even where the curing process is slowed by colder temperatures, and (3) managing the additional and costly processes of heating and protecting concrete during curing. This report reviews the concrete maturity method, describes the technology, describes field observations, and discusses potential benefits of using the concrete maturity method and technology in very cold climates.

Kim, Y.S., C.T. Haas, F. Peyret, and Y.K. Cho, *Transportation Research Circular: Automation in Transportation System Construction and Maintenance*, Transportation Research Board, National Research Council, Washington, D.C., 2000, 28 pp.

The main objective of this Circular is to provide a summary of emerging technologies for automated transportation system construction and maintenance. It is directed toward people in this field so they can keep up with new technologies. The Circular first gives a description of the state-of-the-art enabling technologies for automation in this area. It then introduces several classes of automated systems in applications such as earth moving, compaction, and road construction and maintenance.

Koehler, D.J. and K.J. Majchrowski, *Applications of Automatic Identification Data Collection Systems in the Construction Industry, Proceedings of INCITE 2000 Conference,* Hong Kong, 2000 [Online]. Available: www.bre.polyu.edu.hk/crc/incite2000/Theme2/018.doc.

The integration of Automatic Identification and Data Collection (AIDC) systems into the manufacturing, distribution, and retail industries has resulted in improved competitiveness and profit. Many construction companies have implemented AIDC systems for specific applications such as tool and equipment management; however, the entire construction industry has been slow in developing AIDC systems to be used as part of an IT infrastructure. By using the experiences gained in the design of AIDC systems for the manufacturing, distribution, and retail industries, and the continued development of cost-effective AIDC systems hardware, the opportunities are unlimited for the development of AIDC systems for the construction industry. The purpose of this applied research project is to develop AIDC systems applications for both office and field management activities. The focus is on the development of real-time production data that can be used both by office management for estimating and scheduling purposes and by field management for generating labor and production reports. The data that are collected can also be used for tool and equipment management, consumable and field materials control, scheduling, estimating, purchasing, and accounting. Incorporating AIDC systems technology at the construction site decreases data collection time and increases accuracy, especially repeat activity data. Radio frequency data communication, wide-area networks, and project-specific websites all contribute positively to the construction management process, especially in areas of decision making, validity, reliability, and real-time excellence. It includes return-on-investment information.

Kondratova, I., "Voice and Multimodal Technology for the Mobile Worker," *ITcon*, Vol. 9 (Special Issue), 2004, pp. 345–353.

The availability of real-time, complete information exchange with the project information repository is critical for decision making in construction, as information frequently has to be transmitted to and received from the project repository right on site. Information and communication technology, specifically wireless communications through mobile devices, is seen as a key enabler of leading edge, innovative, and powerful field solutions. However, the widespread use of mobile devices is limited by antiquated and cumbersome interfaces. Speech recognition, along with VoiceXML technology on handheld smart devices, should play a major role in overcoming user interface limitations for mobile devices and improve their usability for industrial field applications. This paper discusses the advantages of using VoiceXML technology for voice-enabled, construction field applications. It presents a pilot application of voice technology for inventory management, and outlines the direction of future research in the area of voice and multimodal communications that enable information mobility in the AEC industry.

Koo, B., *Formalizing Construction Sequence Constraints for the Rapid Generation of Scheduling Alternatives*, *CIFE Technical Report No. 155*, Ph.d. dissertation, Department of Civil and Environmental Engineering, Stanford University, Stanford, Calif., 2004.

The goals of this research were threefold: (1) develop a representation of sequencing rationale that enable planners to describe their rationale for constraints and the classifications they make for different types of sequencing rationale, (2) develop a mechanism that leverages the representation to infer the role and status of activities automatically, and (3) develop a process that supports planners in using the representation and mechanism to develop sequencing alternatives correctly and rapidly. Accomplishing these goals posed unique challenges. The representation needs to model a classification schema that correctly classifies the different types of specific constraints (e.g., damaged by and protected by) in construction schedules with respect to their role and flexibility. The mechanism needs to identify unique paths between activities in a Critical Path Method network and correctly classify activities based on the role and flexibility of the individual constraints in these paths. The process needs to model generically how planners use the role and status of activities to identify which activities to delay and how to prioritize activities when developing sequencing alternatives.

Laurie, S., "TiVo Files Patent for RFID Personal Video Recorder," *TechWeb News*, 2005 [Online]. Available: http://www.techweb.com/wire/hardware/174401408;jsessionid=E4OPC03131X EAQSNDBGCKHSCJUMEKJVN.

LCI Research, The Lean Construction Institute, Louisville, Colo., website, n.d. [Online]. Available: http://www.leanconstruction.org/ [accessed May 25, 2006].

Levinson, M., "The RFID Imperative," *CIO Magazine*, Dec. 1, 2003.

RFID technology is going to generate mountains of data about the location of pallets, cases, cartons, totes, and individual products in the supply chain. It will produce oceans of information about when and where merchandise is manufactured, picked, packed, and shipped. It is also going to create ample numbers telling retailers about the expiration dates of their perishable items—numbers that will have to be stored, transmitted in real time, and shared with warehouse management, inventory management, financial, and other enterprise systems. Applications of RFID technology are also going to need to rely on a new kind of computing architecture known as edge computing, in which vast amounts of processing will take place at the edges of the enterprise's network rather than in corporate data centers.

Li, L., "Maintenance of a Hypertext-Based Electronic Reference Library for a Public Transit Agency," Master of Science, Civil Engineering (Construction Engineering and Management), Iowa State University, Ames, 2002.

Liapi, K.A., "4D Visualization of Highway Construction Projects," *Proceedings of the Seventh International Conference on Information Visualization* (*IV'03*), Los Alamitos, Calif., July 16–18, 2003.

Visualization of transportation projects has been shown to be a very effective way of communicating information between interested project parties. In reviewed applications, visualization has been used primarily for communicating information on the geometric design or as photorealistic representations that place transportation projects within their existing or envisioned built or natural context. A review of examples of transportation visualization also indicates that visualization methods are mostly application specific. This paper focuses on the use of visualization during the construction process of highway projects to facilitate collabora-

tive decision making on construction scheduling and traffic planning. For the visualization of construction scheduling and traffic planning a 4D technology that makes use of a comprehensive 3D project database is proposed. The same 3D database can also be used for the development of photorealistic animations that can facilitate the dissemination of traffic measures information to the traveling public during construction. This approach has been used during the construction of a section of a large-scale highway interchange project in Dallas, Texas.

Lin, L.-S., "Application of GPS RTK and Total Station System on Dynamic Monitoring Land Use," Presented at the XXth ISPRS Congress, Istanbul, Turkey, July 12–23, 2004.

The GPS is an all-weather, space-based navigation system. The real-time kinematic (RTK) positioning is one of the most popular topics in civilian applications. Normally, RTK can be used to collect the land-use change information successfully and quickly. However, RTK does not work in some cases, such as in urban areas or under trees. In those instances, classical terrestrial methods, such as total station systems, can be used to aid RTK, because the collected land-use change information using either RTK or total station system will be entered to an existed land management system. Hence, the user can classify the land-use change styles of a specific region into a certain number of groups from the point view of GIS. To reduce the field surveying works of RTK and/or total station, as well as collect the spatial information of the interested land-use change region promptly and accurately, it is necessary to design an optimized and effective field surveying procedure by means of analyzing the land-use change styles and environmental characteristics of the specific region. Based on this concept, a study project has been undertaken at the National Cheng-Chi University (NCCU). The following issues will be addressed in this project: (1) performance comparisons between using RTK and using total station system on land-use data capture and updating in terms of accuracy, speed, etc.; (2) land-use change styles analysis on the interested regions; (3) design of an effective land-use change spatial information collecting procedure using GPS based on the land-use change styles; and (4) converting collected land-use change data to GIS-compatible files. The campus of NCCU was selected to test the performances of RTK and total station system on land-use change data collection. The cadastral maps (on different times) of Mu-Za district of Taipei City were analyzed to find the possible land-use change styles. Preliminary results indicate that: (1) the horizontal accuracies of RTK and total station system are 14 mm ± 4 mm and 163 mm ± 63 mm, respectively (the coordinates of checkpoints were determined using static GPS); (2) the time required for one point determination using RTK or total station system are about 15 s and 240 s, respectively; (3) the land-use change styles of Mu-Za district can be classified into three main types of polygon (each main type may have two or three styles); and (4) the field surveying works can be reduced significantly if the designed fielding surveying procedures were followed. The main concepts of NCCU project, test procedures, and test results will be described and presented in this paper.

Mallasi, Z., "Workspace Competition: Assignment and Quantification Utilising 4D Visualisation Tools," Presented at CONVR2004: Conference on Construction Applications of Virtual Reality, Lisbon, Portugal, Sep. 14–15, 2004.

This paper addresses a problem arising in many construction sites: the occurrence of workspace interference between construction activities. From a site space planning context, this problem can lead to an inevitable roadblock to the progress of the scheduled construction activities. In real situations, when the spatial congestions occur, they could reduce the productivity of workers sharing the same workspace and may cause health and safety hazard issues. The aim of this paper is to present a computer-based approach to assist site managers in the assignment and identification of workspace conflicts. A new concept of 'visualising space competition' between the construction activities is presented. The concept is based on a unique representation of the dynamic nature of activities' execution workspace in 3D space and time. An innovative computer-based tool dubbed PECASO (Patterns Execution and Critical Analysis of Site-space Organisation) has been developed. The emerging technique of 4D visualization has been chosen to yield an interesting 4D space planning and visualization tool. A multi-criteria function for measuring the severity of the workspace congestions is designed, embedding the spatial- and schedule-related criteria. The paper evaluates the PECASO approach to minimize the workspace congestions using a real case study and concludes that the PECASO approach reduces the number of competing workspaces, as well as the conflicting volumes between occupied workspace, which supports in decision making to decide better execution strategy for a given project schedule. The PECASO tool introduces a new way of communicating the program of work and is expected to be a useful element of the future 4D space planning tools.

Mallasi, Z. and N. Dawood, "Development of VRML Visualization with AutoCAD," Presented at CONVR 2003, Virginia Polytechnic Institute and State University, Blacksburg, Sep. 24–26, 2003.

A feasible approach for supporting VR visualization within the AutoCAD ADT environment is presented. This approach is founded on a standardized representation of the 3D CAD building components, which offers many automation advantages if compared with the existing VR visualization methods. This paper describes the visualization development of a VRML interface built as an add-on to AutoCAD that reuses the original CAD geometrical construction data. The interface is used within the PECASO system for generating effective 4D VR visualization of construction processes in space and time. The core aspect of this integration relies heavily on the appropriate interpretation of the 3D CAD modeling environment to VRML (i.e., converters library). The overall conceptual scheme, detailed procedures, and selected VR visualization examples are shown. Finally, the paper highlights the added value from using the VRML approach, as there is greater demand for integrating CAD with VR technology.

Martello, N., "Stakeless Grading at Chicago Supermall," *Grading & Excavation Contractor*, Nov./Dec. 2001.

Parking lots always present a challenge to earthmoving contractors. Their irregular surfaces require extensive grade checking, and traditional rotating laser systems cannot be employed for machine control. Machine operators now skillfully grade these surfaces quickly and easily with the use of GPS for machine guidance, one of the most innovative areas of today's construction industry.

McCormack, C., "Construction-Site Webcams Save Money, Time for Team," *Retail Construction Magazine*, Spring 2002, pp. 64–68.

A common misconception is that live images on the web provide something similar to television. They do not. The Internet today does not have the speed to broadcast a television-quality signal, although most webcams are based on video technology.

McGrath, D., "Report: RFID Production to Increase 25-Fold by 2010," *EE Times Online*, 2006.

Messner, J.I. and M.J. Horman, "Using Advanced Visualization Tools to Improve Construction Education," Presented at CONVR 2003, Virginia Polytechnic Institute and State University, Blacksburg, Sep. 24–26.

With recent advances in software applications and computer display technology, it is now possible to place construction students within a large-scale, immersive projection display that allows them to experience and experiment with a 3D, full-scale virtual model of a construction project. This advanced visual communication can significantly improve the ability of students to comprehend, learn, and gain experience with reviewing designs for constructability and planning the construction of complex building and infrastructure projects.

Michishita, R., T. Sasagawa, and P. Gong, "Concrete Surface Temperature Mapping and Anomaly Detection with Airborne Thermal

Remote Sensing," Presented at ISPRS 2004: XXth ISPRS Congress, Istanbul, Turkey, July 12–23, 2004.

Erosion control is one of the most important land development policies in Japan. Corrosion of concrete structures and associated structural failures can be seen in complex urban areas owing to the difficulties in detection and maintenance. It is particularly true along transportation systems where retaining walls along highways are unstable. Early detection of such corroded spots possibly will prevent a significant amount of structural failures and loss. The objective of this study is to develop a temperature mapping algorithm that detects such anomalies in concrete structures through airborne thermal remote sensing. A new airborne thermal sensor, Thermal Airborne Broadband Imager, available at PASCO Corporation, is used to acquire thermal data at 0.1°C thermal resolution and with 1.5-m resolution for a study site in Japan. The shadow effect on radiant temperature was analyzed. The statistical *T*-test was used as a measure in detecting concrete anomalies and proved to be effective.

Miller, R., "Web 2.0 Day Three: Silly Business Ideas," *NewsForge*, 2005 [Online]. Available: http://business.newsforge.com/article.pl?sid=05/10/07/202201.

This article discusses the making of "mediascapes" for GPS-enabled, wireless-equipped PDAs and other handhelds. Users will be able to listen to neighborhood stories and information about the any place through earbuds, instead of listening to the actual neighborhood sounds.

Millner, J., M. Hale, P. Standen, and N. Talbot, "The Development and Enhancement of GNSS/GPS Infrastructure to Support Location Based Service Positioning Systems in Victoria," Presented at the 2004 International Symposium on GNSS/GPS, Sydney, Australia, Dec. 6–8, 2004.

Mills, T.H. and R.R. Wakefield, "Modernizing Bridge Safety Inspection with Process Improvement and Digital Assistance," Virginia Polytechnic Institute and State University, Blacksburg, 2004.

This research effort was developed to record and analyze the Virginia DOT bridge/structure inspection processes as an aid to modernizing and automating these inspection processes through the use of mobile PC devices such as Palm/PPCs and other wearable computing devices. The research was conducted using an informal conversational interview process coupled with direct observations to match the perceived processes with actual processes. Once the interviews and observations were completed, work flows were mapped and analyzed for operational bottlenecks and process improvement opportunities. The results of the mappings and a comprehensive literature review were used to analyze the existing work processes. New process transformation maps were created and overlaid on current mappings to complete a transformation model.

Moselhi, O.E.S. and S. El-Omari, "The Use of 3D Scanners for Automated Progress Reporting on Construction Activities," Presented at the 2005 AACE International Transactions, New Orleans, La., June 2005.

The efficiency of integrating cost and time tracking and control functions depends primarily on the accuracy and timely collection of actual data. The earned value (EV) concept developed under the cost/schedule control system criteria by the U.S. Department of Defense is considered an effective tool to monitor project performance. Emerging technologies have been behind initiatives to automate the process of data acquisition needed to perform EV analysis. A control system was developed almost a decade ago using bar code technology to automate project data acquisition and thereafter processing these data for integrating cost and schedule control. Limiting data acquisition to bar code technology has its drawbacks because of the harsh conditions of construction sites because the bar code tags can likely be damaged. Others worked on automated technologies such as pen-based computers, RFID, laser distance and ranging (LADAR), and multimedia technology. This paper discusses the process of implementing the LADAR technology as part of an under-development control system that automates the process of data acquisition for efficient EV analysis. LADAR is used to scan construction items, and then process the scanned data with the software application PolyWorks. The processed data assist in determining work progress, vis-à-vis percent complete needed to generate the EV analysis and reported progress on construction sites.

"Moving Dirt Has Become a Science, Not a Crap Shoot," *Engineering News-Record*, editorial, 2006 [Online]. Available: http://enr.ecnext.com/free-scripts/comsite2.pl?page=enr_document&article=opedar060410.

Using GPS, the process of balancing earthwork—or making sure contractors do not import or export inordinate amounts of material on a site—is executed more easily. Contractors are more certain of their estimates, designers more frequently have the satisfaction of seeing finished projects that closely reflect their original designs, and owners often can more quickly obtain better facilities for the price.

Mower, J.E., "Implementing an Augmented Scene Delivery System," Presented at the International Conference on Computational Science, Amsterdam, The Netherlands, Apr. 21–24, 2002.

This paper addresses the core issues confronting the design and use of an augmented scene delivery system (ASDS). An augmented scene is a real-time, interactive, symbolized, perspective view of an environment that serves as a graphical index to an underlying spatial database. It allows a person in the field to interpret and navigate through the environment without reference to an external map. Augmented scenes will enable users with underdeveloped map use skills to effectively interpret and analyze their environment in professional, educational, and recreational contexts. This paper discusses an ASDS implementation that acquires imagery from a user-controlled webcam. It focuses on issues of data sampling and representation.

Navon, R., Y. Shpatnitsky, and E. Goldschmidt, "Model for Automated Road-Construction Control," Presented at the International Symposium on Automation and Robotics in Construction, 19th (ISARC), Gaithersburg, Md., Sep. 23–25, 2002.

A survey of current practices revealed that very little control is normally done in earth-moving management. A model to control road construction projects was developed. The model is based on the concept of automatically measuring performance, by measuring locations at regular time intervals, and converting them into controlled parameters. According to this concept, control algorithms convert the measured locations to produce two types of real-time control data: progress and productivity. Locations are measured with a GPS. Field experiments conducted with the prototype of the GPS measurement system prove its suitability as a Location Measurement Module.

Nielsen, J.S., *The Myth of Leadership: Creating Leaderless Organizations*, Davies–Black Publishing, Palo Alto, Calif., 2004.

Northcutt, G., "Boost Grading Precision and Productivity with 3D Technology," *Grading & Excavation Contractor*, July/Aug. 2004.

When grading and excavation contractors talk about automated grade control systems these days, they often focus on 3D systems—the ones that have revolutionized the way contractors move dirt by eliminating the need for stakes, hubs, and string lines, and the time and labor to place and move them. They are allowing equipment operators to grade with a degree of accuracy, speed, and simplicity unheard of just a few years ago. In doing so, these systems are increasing productivity dramatically.

Nuntasunti, S. and L.E. Bernold, "Beyond Webcam: A Site-Web-Site for Building Construction," Presented at the International Symposium on Automation and Robotics in Construction, 19th (ISARC), Gaithersburg, Md., Sep. 23–25, 2002.

The use of project website and webcam technology in the construction industry is limited to providing basic information about the project and 24/7 pictures of the site. This paper discusses the promises of a site-based website that serves as the central hub for real-time communication, monitoring, and control in building construction. Such a website offers opportunities that go beyond what is in use today. The paper lists a series of possible applications that have been tested at several construction sites in Raleigh, North Carolina. In addition to helping contractors plan and control the resource flow in real time, the site–website is also used as a tool for creating daily reports and visual as-builts, and facilitating rapid problem solving, remote inspection, productivity measurement, on-site security, and communicating with on-site equipment (e.g., in emergencies).

Oloufa, A.A., M. Ikeda, and H. Oda, "GPS-Based Wireless Collision Detection of Construction Equipment," Presented at the 19th International Symposium on Automation and Robotics in Construction (ISARC), Gaithersburg, Md., Sep. 23–25, 2002.

This paper reports on research related to avoiding collisions in construction sites using differential GPS technology. In this project, the researchers developed and implemented a system where GPS technology was used in tracking a single vehicle and relaying its information to a central server. Using another simulated vehicle, the server evaluated collision scenarios and sent cautionary messages to the roving vehicle if a collision is impending. The paper concludes with a summary of the application, along with a discussion of the limitations of GPS technology and the required augmentation by other technologies.

O'Brien, K.J., "Now, a Laptop You Can Hold in Your Hand," *New York Times*, March 9, 2006.

O'Malley, P.G., "It's Up to You: Contractors Talk About Machine Guidance and Control," *Grading & Excavation Contractor*, Sep./Oct. 2003.

O'Malley, P.G., "Troubleshooting Machine Control: Contractors Talk About Making the Most of 3D GPS," *Grading & Excavation Contractor*, March/April 2005.

The jury may still be out, but contractors and industry leaders in machine control, including Trimble, Topcon, Leica, and now Caterpillar—which has hit the market with AccuGrade, factory-installed integrated grade control—are projecting that 3D automated systems will be the long-term name of the game for dirt contractors. The technology will affect not only how dirt is moved, but also what happens before the earthmoving begins and how machine operators function.

"OxBlue: A New Web Cam Service Increases Jobsite Security," *Constructor Magazine*, Sep./Oct. 2005.

Product review and case study (commercial building) of OxBlue Web Cam.

Paiva, J.V.R., "The SCOOP on Earthmoving," *SitePrep Magazine*, Apr. 2004, pp. 2–5.

An important but easily overlooked aspect of the new machine control landscape is the Digital Terrain Model (DTM). Just because it does not have the snazzy presence of GPS or some other machine-based personality, but instead exists in the digital realm, this important way of bringing the relevant geodata to the worksite should not be ignored. The concept of the DTM is not new, having become prominent with advanced software for earthwork that quickly followed advances in electronic surveying technology. It is important for contractors to understand that the use of DTMs is essential for construction machine control and it is equally vital for surveyors and data managers to help contractors understand the importance of correctly implemented DTMs.

Patel, H., M. D'Cruz, S. Cobb, and J. Wilson, *Initial Report on Existing Evaluation Methodologies*, Information Society Technologies (IST), 2004.

This deliverable reports on general issues associated with evaluating VR/VE systems, in particular, and focuses on issues to consider when selecting methods for an evaluation program, constraints on the selection of methods, difficulties in evaluating VR/VE, and human factors issues to consider in the evaluation program. This report provides a description of methods that have been used to evaluate VR/VE. The advantages and disadvantages of some of the main evaluation methods and approaches are also included, as is information on the INTUITION partners' personal experience of using some of these evaluation methods.

Paynor, L., "Seeing the Future: Stakeless?!" *SitePrep Magazine*, Apr. 2004, pp. 6–10.

3D data are making sense to an increasing number of contractors and surveyors across the nation. Construction machine control systems—which put design surfaces, grades, and alignments inside the cab—are becoming the wave of the future. More and more earthmovers, construction firms, and DOTs are depending on the advanced efficiencies, time savings, and greater profits machine control can provide. Machine control depends on accurate 3D modeling to guide the blades, buckets, wheels, and hoes to the precise position required. As an example of this, look at some of the innovative firms using machine control today.

PDA Applications Pilot Project Summary Report, Maine DOT Information Systems Division, Augusta, 2004.

Applications developed for the PDA or remote data collection need to undergo the same process analysis as other applications and must be written by programmers with a broad understanding of the technology. Once requirements are known, an application that requires four forms, a database, synchronization methods, and digital image collection would take about three months to develop. Consideration should be given to the following before requesting an application.

PDT 8000, Symbol Technologies, Baltimore, Md., 2002.

The PDT 8000 is a compact, ergonomic Pocket PC mobile computing device with integrated wireless communications and bar code data capture. Created to meet the needs of mobile workers, the PDT 8000 is rugged enough for use anywhere along the supply chain, and provides the speed, power, and functionality needed to effectively manage data at the point of activity.

Post, N.M., "Collaborative Construction: 74% of Architects Use Some Level of 3D Digital Modeling, Says Survey," *Engineering News-Record*, June 5, 2006.

This 28-question, on-line survey was conducted from December 3, 2005, to January 6, 2006. The initial sample of American Institute of Architects members included 54,744 individuals. Of the respondents, 36% are in firms of fewer than seven employees, and 33% had gross billings of $500,000 to $5 million in the last completed fiscal year. Of participants, 58% spent less than 5% of their annual operating budget for the last fiscal year on 3D modeling/BIM technology.

Post, N.M., "Collaborative Construction: First Standard for 3D Modeling Due by Year-End," *Engineering News-Record*, June 5, 2006.

A basic premise of BIM, says the National Institute of Building Sciences (NIBS), is collaboration by different stakeholders at different phases of the life cycle of a facility. The stakeholders will insert, extract, update, or modify information in the BIM to support and reflect on the roles of each stakeholder. The BIM "is a shared digital representation founded on open standards for interoperability," states NIBS in its definition of BIM. The National BIM Standard promotes the business requirement that the model is "interoperable based on open standards."

Post, N.M., "Collaborative Construction: Team Members Seek Ways Out of the Building Modeling Haze," *Engineering News-Record*, June 5, 2006.

A revolution is beginning in the buildings sector and the catalyst is computer-enabled BIM. The coming kinder, gentler BIM business models are expected to produce better buildings, faster, at lower cost, with fewer claims and less agitation. BIM technology "will not only change the existing delivery systems, it will change the job description of most people involved in design and construction," says Barbara Heller, CEO of Design + Construction Strategies, a BIM consultant in Washington, D.C.

Post, N.M., "Rocky Mountain High: Denver's Unfathomable Form Brought in on Time and Budget," *Engineering News-Record*, May 15, 2006, pp. 26–30.

Powers, M.B., "Contractors Scrambling to Master 3D Modeling Technologies," *Constructor Magazine*, 2005 [Online]. Available: http://constructor.construction.com/features/issuesTrends/archives/2005-09-3DModel.asp [accessed May 17, 2006].

Some contractors are using 3D and 4D modeling on their complex projects now and more will adopt the technology as owners start to demand it.

"Project 4D and the Common Point Platform," Common Point, Inc., Mountain View, Calif., n.d. [Online]. Available: http://www.commonpointinc.com/products/brochures/Project4D%20Brochure.pdf.

Marketing data explaining the Project 4D software suite for the Common Point Platform.

Rafter, D., "Boosting Efficiency with Blade Control Systems," *Grading & Excavation Contractor*, Sep./Oct. 2005.

Construction firms both large and small find blade control systems increase productivity.

Roadmap Element 6: Real-Time Project and Facility Management, Coordination and Control, FIATECH, University of Texas at Austin, presentation slides, 2005.

FIATECH Powerpoint slide show discussion includes a section on Intelligent Project Management.

Robinson, K., *Out of Our Minds: Learning to Be Creative*, West Sussex: Capstone Publishing Limited, West Sussex, United Kingdom, 2001.

Rodgers, R.A., *A 4D-CAD Implementation Utilizing J Space Schedule Simulator, Architecture*, Virginia Polytechnic Institute and State University, Blacksburg, Va.

As the AEC industry heads into the 21st century it must evolve to accommodate an increasingly complex, faster-paced environment. With the complexity of building systems increasing while construction operations are being accelerated, the industry must have systems in place to improve documentation, coordination, and communication both in the planning stages of a project and in the field. These challenges that today impact a company's profit margin may in the future dictate their survival in an increasingly competitive market. One of the technologies developed to improve not only the coordination and communication of documents but also the very design and planning of construction projects is 4D CAD. 4D CAD technology integrates the individual components of a 3D CAD model with scheduled activity start and finish dates assigned to its physical systems. 4D CAD allows for a visual simulation of the building's construction viewed through space and the fourth dimension of time. This project and report takes a theoretical design from the schematic stages to the final 4D CAD model. This model provides the unique opportunity to explore the process of creating a 4D CAD model from the initial stages of the project's conception. This project and report will explore how planning the project's documentation production for constant interaction and final integration into a 4D model affects the coordination and completeness of this documentation. This process and final model are intended to be an exploration into the possibilities of current 4D CAD technology.

Roe, A., "Building Digitally Provides Schedule, Cost Efficiencies: 4D CAD Is Expensive But Becomes More Widely Available," *Engineering News-Record*, 2002 [Online]. Available: http://www.dprinc.com/news/news_enr20020225.cfm.

In the ongoing quest to improve project planning and anticipate field problems before they occur, a growing number of construction professionals are using computer technology to build projects digitally before actual construction begins. 4D CAD, which combines 3D CAD with the time element of scheduling software, is gaining a foothold at construction sites after years of incubation in academia and niche sectors of the construction industry.

Rubin, D.K., "Construction Managers Face Dilemmas with New Tech Tools," *Engineering News-Record*, May 15, 2006, p. 15.

The advent of BIM and 4D design technology offers construction managers (CMs) exciting new project management tools; however, some worry about liability and design ownership issues, particularly on federal work. The U.S. General Services Administration is adopting BIM technology on more projects that will affect its CMs, said Steven Hagan, director of GSA's Project Knowledge Center. "CMs are often just information managers. We want you to be avid participants."

Ruggedized Mobile Computer Specifications, In *Whitepaper*, LXE, Inc., Norcross, Ga., n.d.

Ruggedized mobile computer specifications by LXE, Inc.

Rybka, R., "How Machine Control Systems Work," *Grading & Excavation Contractor*, May/June 2006.

Technology has leaped ahead of our ability to understand machine components and how they operate. The rapid advancement of technology puts many contractors in a dilemma. It is hard to make an informed purchase decision and be confident that an investment in technology will pay off when you do not quite understand how things work

Rybka, R., *Making the Grade with GPS*, Dixie Contractor, an Associated Construction Publication, 2006 [Online]. Available: http://www.acppubs.com/index.asp?layout=articlePrint&articleID= CA6332764.

Gary's Grading is one of several contractors across the nation who is advocating major changes in DOT specs and policies. The proposed changes will accommodate the use of GPS technology on DOT highway projects. Current specifications require specialized machines for subgrade preparation and labor-intensive field engineering for grade control. Changes to allow the use of GPS equipment as an alternative to conventional equipment and methods will have a major impact on our nation's transportation industry. Highways will be built faster and ride smoother.

Sabol, S.A., *NCHRP Synthesis of Highway Practice 300*: *Performance Measures for Research, Development, and Technology Programs*, Transportation Research Board, National Research Council, Washington, D.C., 2001, 97 pp.

Sacks, R., R. Navon, and E. Goldschmidt, "Building Project Model Support for Automated Labor Monitoring, *Journal of Computing in Civil Engineering*, 2003.

In current project control practice, deviations from planned performance can only be reported after significant time has elapsed. Manual monitoring on construction sites is costly and error prone. Consequently, an automated model for monitoring labor inputs, based on automated data collection (ADC), offers a solution to the problem. Integration with a computerized building project model (BPM), including the physical geometry of the building, the resources active in its execution, and the planned construction activity schedule, is essential for the operation of such a model. Integration with an existing BPM requires that the BPM be expanded to support interpretation and accumulation of the monitoring results. To this end, appropriate project model classes and relationships have been implemented and tested. Experimental data were collected, using an ADC system, from the jobsite of a reinforced concrete building. The data were processed, within the BPM, with the aid of a prototypical location interpretation module.

Saidi, K., *Possible Applications of Handheld Computers to Quantity Surveying*, Ph.D., University of Texas at Austin, 2002.

Sampaio, A.Z., P.G. Henriques, P.S. Ferreira, and R.P. Luizi, "Using 3D Virtual Models in Civil Engineering Training: Interacting with the Construction Processes," Presented at the 8th Generative Art Conference 2005, Milan, Italy, Dec. 15–17, 2005.

The use of VR techniques in the development of educational applications brings new perspectives to the teaching of subjects related to the field of civil construction in the civil engineering domain. To obtain models, which would be able to visually simulate the construction process of two types of construction work, the research turned to the techniques of geometric modeling and VR. The applications developed for this purpose are concerned with the construction of a cavity wall and a bridge. These models make it possible to view the physical evolution of the work, to follow the planned construction sequence, and to visualize details of the form of every component of the works. They also support the study of the type and method of operation of the equipment necessary for these construction procedures. These models have been used to distinct advantage as educational aids in first-degree courses in civil engineering.

Sawyer, T., "Soaring into the Virtual World: Build It First Digitally," *Engineering News-Record*, Oct. 10, 2005.

Bentley's ProjectWise collaboration servers were used to circulate the architect's Microstation model. Users could see it with a free viewer. NavisWorks design reviewer and 3D model coordinator integrated new geometry developed by subcontractors in other programs and ran collision detection on the results. Software included SDS/2 for steel detailing, QuickPen for mechanical planning, InteliCAD for HVAC, and Autocad and various Autocad third-party products, reports Samir Emdanat, Ghafari's manager for advanced technologies. He says NavisWorks does not always bring in every bit of associated data, but it brings in enough. "It's the best you can do with the supply chain right now."

Schefcick, M., G. Cheok, and A. Lytle, *Laser Scanning Measurement Assurance: Project Panel Review*, FIATECH, University of Texas at Austin, 2005.

Schneider, M., *Radio Frequency Identification (RFID) Technology and its Applications in the Commercial Construction Industry*, University of Kentucky, Lexington, 2003.

This is a report of RFID technology and its potential applications in the commercial construction industry. RFID technology offers wireless communication between RFID tags and readers with non-line-of-sight readability. These fundamental properties eliminate manual data entry and introduce the potential for automated processes to increase project productivity, construction safety, and project-cost efficiency. Construction contractors, owners, and material suppliers that believe technology can further develop methods and processes in construction should feel obligated to participate in RFID studies for the advancement of the construction industry as a whole.

Schreyer, M., T. Hartmann, M. Fischer, and J. Kunz, "CIFE iRoom XT Design & Use," In *CIFE Technical Report No. 144*, Stanford University, Stanford, Calif., 2002.

During the design and planning process of civil engineering projects, a variety of different computer applications are used. Each of these programs models a subset of the overall project's context. For the interdisciplinary tasks discussed in project meetings it is important to identify the existing interrelations between these sub-models of the different applications. The hardware and software for interactive workspaces can be used to link the different application models by modeling the mutual relationships between shared data and can therefore support the decision process through cross-application functionalities. To achieve this, the workspace has to be able to distribute data between the connected applications.

Schriener, J., "New Version of Document Software Gives Viewers Access to 3D," *Engineering News-Record*, Jan. 30, 2006 [Online]. Available: http://enr.ecnext.com/free-scripts/comsite2.pl?page=enr_document&article=neinar060130b.

Adobe Systems Inc., San Jose, California, introduced Adobe Acrobat 3D on January 23, 2006. It allows people using the free Adobe Reader viewer to interact with 3D models created in a variety of CAD software applications and converted to Adobe's PDF format. Anyone with the Adobe Reader 7.0.7 can view, enter comments, make cross sections, animate, and add textures and materials to elements of 3D CAD drawings, as long as the creator of the original PDF file has enabled those capabilities

Schwegler, B., M. Fischer, and K. Liston, "New Information Technology Tools Enable Productivity Improvements," Presented at North American Steel Construction Conference, AISC, Las Vegas, Nev., Feb. 23–26, 2000.

In this paper the authors argue that project information should be presented visually in 3D and 4D models to reach as many project stakeholders as possible as effectively as possible. When based on the input of many stakeholders, these models represent possible project alternatives completely, accurately, and in an easy to understand manner. They enable all project team members to leverage their own project data and the data of others. The current document-centric paradigm, however, does not support the rapid and economical construction of these models. Hence, this paradigm needs to be complemented with a model-based approach to create, share, and use project information. These project models will enable project team members to explore many design and construction alternatives rapidly to work out potential problems before work is put into place in the field. They will also enable e-commerce to improve procurement of materials and services. Electronic information exchange standards will greatly facilitate the creation and maintenance of these project information models throughout a project's life cycle. The CIMsteel integration standards for the steel industry are the most advanced standard in the general building industry. Thus the steel supply chain is in a position to be the first supply chain to reap the aggregate benefits from model-based life-cycle engineering.

Schwegler, B.R., M.A. Fischer, M.J. O'Connell, R. Hänninen, and J. Laitinen, "Medium- and Long-Term Benefits of Information Technology in Construction," *CIFE Working Paper No. 65*, Center for Integrated Facility Engineering (CIFE), Stanford University, Stanford, Calif., 2001.

IT has been on a long slow path of implementation in the construction industry. The use of CAD is now the industry standard as is the use of e-mail, the World Wide Web, and a wide variety of personal computing software. The use of e-commerce services is growing and appears to be on the way to widespread commercial adoption, as are some data and document exchange standards. In spite of these successes, the AEC industry has been remarkably resistant to the cataclysmic business changes of consolidation, productivity improvement, and globalization that have overtaken the automotive, aerospace, and discreet manufacturing industries. In this paper, the authors explore some of the near and long-term IT challenges facing the construction industry and suggest how new IT tools will enable three crucial new capabilities with the potential to create the profound changes seen in these other industries. First, new tools like 4D have grown out of the tradition of engineering CAD design. These new tools allow simulations of construction processes as well as visual simulations of the individual components. Second, transaction performance measurements [e.g., quantities of transactions and auditable trails of requests for information (RFIs), submittals, change orders, and deficiency correction notices] that were up to now too expensive and time consuming to do will become commonplace and virtually free. Third, improved data sharing with flexible product model schemas will permit the development of new contracting relationships, more geographically dispersed teams, and more tightly integrated supply chain performance. Depending on the investment time horizon, the specific challenges and tools available may change, but the overall direction is unmistakable. The AEC industry is about to experience a profound change: leaner organizations, more consistent and rigorous performance metrics, and relentless productivity improvements. The net result of these changes should also be increased profitability for those who are successful at mastering the new IT tools with the promise to enable these changes. This paper summarizes the ongoing research, development, and implementation of these new capabilities in early-adopter organizations and provides a roadmap to the short-, medium-, and long-term adoption by the AEC industry.

Scott, D.L., *Wall Street Words: An A to Z Guide to Investment Terms for Today's Investor*, Houghton Mifflin Company, Boston, Mass., 2003.

Seddon, J., "Machine Control in Urban Environment," *New Zealand Institute of Surveyors Survey Quarterly*, Vol. 45, 2006, pp. 18–24.

There are essentially two types of systems within the 3D machine control family: machine guidance and machine control. Machine guidance is a manual system where the operator controls the machine's hydraulic rams. The machine control system however is fully automatic in the sense that the machine's hydraulics is controlled automatically.

Seelmeyer, J., "Web Cams a New Tool for Managers of Construction," *Northern Nevada Business Weekly*, 2005.

Three webcams provide a steady stream of photographs of the construction to anyone who logs onto Washoemed.com; however, the big value of the photos is their use in management of the $240 million project.

Sheppard, L.M., "Virtual Building for Construction Projects," *IEEE Computer Graphics and Applications*, Vol. 24, No. 1, 2004, pp. 6–12.

4D CAD technology in its simplest form links 3D models to schedules. More advanced versions link costs and other data. Instead of just reviewing printed flow diagrams, users can visualize the construction sequence as a movie or animation. This avoids conflicts in scheduling and resolves safety issues (such as erecting steel over where people work) before actual construction begins.

Shiratuddin, M., J.L. Perdomo, and W. Thabet, "3D Visualization Using the Pocket PC," Presented at ECPPM: eWork and eBusiness in AEC, Portoroz, Slovenia, Sep. 9–11, 2002.

Shiratuddin, M. and W. Thabet, "A Framework for a Collaborative Design Review System Utilizing the Unreal Tournament (UT) Game Development Tool," Presented at the 20th CIB W78: Conference on Information Technology in Construction, Auckland, New Zealand, Apr. 23–25, 2003.

Shiratuddin, M. and W. Thabet, "Implementation Issues of a Design Review System Using Virtual Environment," Presented at the ASCE Construction Research Council, PhD Research Symposium, Nashville, Tenn., Nov. 14, 2003.

Shiratuddin, M. and W. Thabet, "Issues in Implementing a Virtual Environment-Based Design Review System," Presented at CONVR 2003: Conference on Construction Applications of Virtual Reality, Virginia Polytechnic Institute and State University, Blacksburg, Va., Sep. 24–26, 2003.

"Simplify Your Life: Visit Your Construction Sites Online," OxBlue Corp., Atlanta, Ga., 2002.

The use of webcams can improve construction management and help to avoid critical path delays. A webcam gives you the ability to show your projects to potential tenants, investors, and consultants anywhere in the world. You can even have the peace of mind that comes from being able to watch your project's progress online.

Slattery, K.T. and A. Kharbanda, "Computer Vision in Construction—Developing an Application to Monitor Steel Erection," Presented at the 42nd Annual Conference of the ASC, Colorado State University, Fort Collins, Apr. 20–22, 2006.

Computer vision technology can be used to analyze digital photographs of construction sites to provide concise reports on project quality and progress. This information is then available to verify the correct placement of materials, study productivity, and monitor safe practices. Implementation is greatly facilitated by a 3D model of the project so the analysis software knows where to look for each entity. An application is being developed and tested to monitor steel erection to demonstrate the feasibility of this approach. Algorithms to calculate the camera location from known points, implement off-the-shelf computer vision software to detect edges, and search for each structural member are discussed. The results of an image analysis of a partially completed structure are presented.

Smith, S., "4D CAD Goes Beyond Mere Representation," *AEC Vision*, Vol. 7, 2001 [Online]. Available: http://www.aecvision.com/October2001/1_feature_full.pdf.

To save time and money, 4D offers simulation—beyond mere representation—to a full-scale simulation that includes the 3D model plus time. This concept is particularly appealing to those who handle extremely complex projects, such as plant design, nuclear power, and retrofit construction projects. The goal is to build a model that is as similar to the real project as possible, so that you can test it and change it and see the consequences of your actions—before committing real materials and real people to the actual building process of the real construction project.

Song, D., Q. Hu, N. Qin, and K. Goldberg, "Automating Inspection and Documentation of Remote Building Construction Using a Robotic Camera," Presented at the IEEE International Conference on Automation Science and Engineering, Edmonton, AB, Canada, Aug. 1–2, 2005.

When constructing buildings, frequent inspection and detailed visual documentation are important but may not be feasible in remote or dangerous environments. A networked robotic camera system is described that can automatically monitor construction details and allow remote human experts to zoom in on features as construction proceeds to archive the construction process over time, thereby reducing travel cost and human risk. System architecture, interface design, data structures, and algorithms for such systems are described, and initial experimental results from cameras at two outdoor construction sites are reported.

Specifications of Computer Deliverable Contract Plans, Missouri DOT, Jefferson City, Oct. 1, 2000 [Online]. Available: http://www.modot.org/pdf/business/Computer_Deliverable_Contract_Plans_2000.pdf.

A discussion of specifications of computer deliverable contract plans.

Staub, S. and M. Fischer, *Constructability Reasoning Based on a 4D Facility Model*, 2006 [Online]. Available: http://www.civil.ubc.ca/faculty/Staub-French/4D_Constructability.pdf [accessed May 19, 2006].

Improving the constructability of a facility design is a key concern for owners, designers, and builders of facilities. Prior research has shown that a product model based on a 3D CAD model of a facility can support constructability reasoning to assist a project team in identifying constructability issues. This paper shows how a 4D facility model (3D plus time) improves constructability reasoning. A 4D model helps expose constructability problems related to access, temporary support, availability of work space, and completion of prerequisite work. The paper explains the 4D model and its attributes in detail and gives specific examples of automated constructability reasoning. It discusses the advantages of 4D models over 3D models for recognizing constructability problems in the planning and design stages of a project.

Staub, S., M. Fischer, and M. Spradlin, "Industrial Case Study of Electronic Design, Cost, and Schedule Integration," *Building Electronically: Construction in the 21st Century*, 1998 [Online]. Available: http://www.nwccc.org/presents/fischer.pdf.

Although most documents are generated electronically, today's project management processes are still characterized by a largely manual exchange of information based on paper documents. Project teams could benefit from software technology that integrates design, cost, and schedule information. Some of these benefits include the automatic generation of quantity take-offs directly from design drawings, improved visualization of construction schedules, improved coordination of construction disciplines, and improved communication between design and construction. This technology has existed for some time and research has shown that it is technically feasible. However, the authors are not aware of a project team that has accomplished design, cost, and schedule integration in a collaborative environment on an actual construction project. The Sequus Pharmaceuticals Pilot Plant is an instance where a project team has implemented design, cost, and schedule integration, and it forms the basis of our case study. On this biotech facility, a design–build team consisting of a design firm, a general contractor, and three subcontractors has jointly developed a common 3D model from the very start of the project to link with cost estimating and scheduling software. The electronic integration of design and cost information was accomplished through the CAD-estimate link developed by Ketiv and Timberline. Design and schedule integration (4D, 3D + time) was accomplished through Jacobus Technology's Schedule Simulator. This case has provided us the opportunity to investigate the status of commercial design, cost, and schedule integration software and to understand the resource requirements necessary to accomplish these tasks on an actual project. This study suggests that owners, designers, and builders of facilities will need to develop new skills and implement organizational changes to take advantage of the benefits offered by this technology and to stay competitive in this changing market. Specifically, general contractors will need to learn how to manipulate 3D CAD models, work more closely with the designers in design development, and provide input on how to model designs in 3D so that the CAD models are more usable by constructors. Subcontractors will also need to learn design software, as they will be performing more detailed design, working more closely with the architects and engineers through the design process, and addressing coordination issues early in design development. Designers will need to focus more on the overall design and coordination of design tasks and less on detailed design. Finally, owners will need to bring a project team together early in the project to capitalize on the benefits of this technology.

Staub-French, S. and M. Fischer, "Industrial Case Study of Electronic Design, Cost, and Schedule Integration," In *CIFE Technical Report No.122*, Stanford University, Stanford, Calif., 2001.

This report describes the efforts of a project team to leverage 3D models for design coordination and constructability analysis, cost estimating, and construction planning to maintain integrated scope–cost–time models during design and construction of a Pilot Plant for Sequus Pharmaceuticals. The authors describe the benefits and shortcomings of the software, the corresponding research issues, and the resource requirements necessary to integrate this information, and also describe the project team's evaluation of this integrated approach, its affect on the project's outcome, and its affect on the roles and responsibilities of each discipline within the project team. This experience on the Sequus project shows that early and simultaneous involvement of project teams including designers, general contractors, and subcontractors in the design and construction of a capital facility coupled with the use of shared 3D models allows project teams to deliver a superior facility in less time, at lower cost, and with less hassle. Although a long functionality wish list was created as part of this report, this case shows that commercial tools that can electronically integrate design, cost, and schedule information provide many benefits to project teams throughout the design and construction process.

Stewart, L., "Startup Quadruples Revenue with GPS Grade Control," *Construction Equipment*, 2005 [Online]. Available: http://www.constructionequipment.com/article/CA6288266.html.

"For GPS grade controls to really work, you've got to have operators who are charged up about the technology and take some pride in using it," says Chrisman. "You can wind up with a real mess on your hands if the accuracies get too far out and the operator thinks, 'It's good enough,' and keeps right on working [the cab display shows when GPS accuracy has degraded because the receiver is not getting signals from enough satellites]."

Stone, W.C., M. Juberts, N. Dagalakis, J. Stone, and J. Gorman, "Performance Analysis of Next-Generation LADAR for Manufacturing, Construction, and Mobility," Building and Fire Research Laboratory, National Institute of Standards and Technology Construction (NIST) Metrology and Automation Group (CMAG), NIST Intelligent Systems Division (ISD), Gaithersburg, Md., 2004.

The NIST CMAG, in cooperation with the NIST ISD, is developing performance metrics and researching issues related to the design and development of a next-generation LADAR (laser radar) sensor that will enable general automation in structured and unstructured environments. This report reviews the basic physics and implementation of various LADAR technologies, describes the problems associated with available "off-the-shelf" LADAR systems, summarizes world-wide state-of-the-art research, and elaborates on general trends in advanced LADAR sensor research and their likely impact on manufacturing, autonomous vehicle mobility, and on construction automation.

Sulbaran, T., "Distributed Virtual Reality Scheduling in Future Construction Companies," *Proceedings of the 2005 ASCE International Conference on Computing in Civil Engineering*, Cancun, Mexico, July 12–15, 2005.

The construction industry is the largest simple production industry in the United States. The importance of the construction industry is not limited to the United States; it plays an important role in the economy of many countries around the globe. However, unlike other sectors of the economy, the construction industry is characterized by slow adoption of new technologies. One of these technologies that has not taken an important role in the construction industry is Distributed Virtual Reality (DVR) environments. There are many reasons that justify the slow adoption of DVR environments in the construction industry, one of which is the lack of understanding of the possible uses of DVR environments within the construction industry. This paper summarizes a variety of possible DVR applications within the construction industry. These DVR applications are framed within one of the most common responsibilities of construction professional scheduling. The DVR applications presented in this paper are intended to spark implementations in future construction companies. Therefore, this paper follows a descriptive methodology, which is used because the main goal is to illustrate the potential applications and impacts of this technology in the construction industry. Because DVR applications have not been widely implemented in the construction industry there is a dearth of statistically significant data to support the benefits of this technology. However, the results of the early developments of this technology summarized in this paper exemplify the potential impacts of DVR environments in the construction industry. Therefore, the DVR applications summarized herein have the potential to help the construction industry move into the future construction industry.

Supporting Railroad Roadway Worker Communications with a Wireless Handheld Computer: Volume 1: Usability for the Roadway Worker, Report DOT/FRA/ORD-04/13.I, Federal Railroad Administration, Washington, D.C., 2004.

This report documents the design and evaluation of a digital communication device intended to improve roadway worker safety and productivity. The goal of the study was to understand the safety implications of new communication devices and to identify usability issues associated with making them effective tools for their operators.

Supporting Railroad Roadway Worker Communications with a Wireless Handheld Computer: Volume 2: Impact on Dispatcher Performance, Report DOT/FRA/ORD-04/13.II, Federal Railroad Administration, Washington, D.C., 2004.

This study is part of a research program to evaluate the human factors implications of computer and communications technology in railroad operations. The FRA's Office of Research and Development sponsored the research, as part of its activities to develop Intelligent Railroad Systems (Federal Railroad Administration 2002).

Sutton, D.R., *TCRP Synthesis of Transit Practice 55: Geographic Information Systems Applications in Transit*, Transportation Research Board, National Research Council, Washington, D.C., 2004, 60 pp.

This synthesis will be of interest to transit practitioners and researchers, including technical staff and transit managers, as well as to vendors of GIS solutions. This report illustrates the value of GIS to transit agencies in service provision and in potential cost savings. The synthesis summarizes the experiences of a variety of transit agencies, with information provided from small- and medium-sized transit operators, as well as from large transit agencies. It documents current practices, effective applications, and challenges. The report covers the full range of transit services including planning, operations, management, IT, and customer service. Included are case studies from five large transit operators that demonstrate a number of innovative uses of GIS, as well as illustrate how GIS is becoming a part of mainstream IT and a core technology in transit information services.

Symbol Technologies, Inc., *PDT 8000 Series Specification Highlights*, 2002 [Online]. Available: http://www.scansmart.com/catalog/pdt8000.pdf [accessed May 15, 2006].

Symbol PDT 8000 ruggedized HHC specifications.

"Temperature Tracking," Identec Solutions, Houghton-le-Spring Co., Durham, United Kingdom, n.d.

Marketing data from Identec Solutions: "The combination of [radio frequency identification] (RFID) technology and temperature monitoring creates the most automatic product integrity and tracking system available."

Townes, D. and B. Alsobrooks, *SEAUPG 2005 Conference*, Nashville, Tenn., Dec. 12–15, 2005.

Tserng, H.P. and J.S. Russell, "A 3D Graphical Database System for Landfill Operations Using GPS," *Computer-Aided Civil & Infrastructure Engineering*, Vol. 17, No. 5, 2002, pp. 330–341.

Landfill space is an important commodity for landfill companies. It is desirable to develop an efficient tool to assist space management and monitor space consumption. When recyclable wastes or particular waste materials need to be retrieved from the landfill site, the excavation operations become more difficult without an efficient tool to provide waste information (i.e., location and type). In this paper, a methodology and several algorithms are proposed to develop a 3D graphical database system (GDS) for landfill operations. A 3D GDS not only monitors the space consumption of a landfill site, it can also provide exact locations and types of compacted waste that would later benefit the landfill excavation operations or recycling programs after the waste is covered.

Tserng, H.P., R.-J. Dzeng, Y.-C. Lin, and S.-T. Lin, "Mobile Construction Supply Chain Management Using PDA and Bar Codes," *Computer-Aided Civil and Infrastructure Engineering*, Vol. 20, 2005, pp. 242–264.

Construction project control aims to effectively obtain real-time information and enhance dynamic control by using information sharing and connecting involved participants of the projects to reduce construction conflicts and project delays. However, extending the construction project control system to jobsites is not considered efficient because using notebooks in a harsh environment like a construction site is not a conventional practice. Meanwhile, paper-based documents of the site processes are ineffective and cannot get the quick response from the office and project control center. Integrating promising information technologies such as PDAs, bar code scanning, and data entry mechanisms, can be extremely useful in improving the effectiveness and convenience of information flow in construction supply chain control systems. Bar code scanning is appropriate for several construction applications, providing cost savings through increased speed and accuracy of data entry. This article demonstrates the effectiveness of a bar-code-enabled PDA application, called the mobile construction supply chain management (M-ConSCM) system that responds efficiently and enhances the information flow between offices and sites in a construction supply chain environment. The advantage of the M-ConSCM system lies not only in improving the efficiency of work for on-site engineers, but also providing the Kanban-like visual control system for project participants to control the whole project. This article also presents a generic system architecture and its implementation.

Turbyfill, J.B. and R.E. Smith, *Cost Savings Estimate for Construction Stakeout Using GPS RTK versus Conventional Total Station/Level and NRTK versus RTK*, North Carolina Department of Transportation, Raleigh, 2005.

The authors have separated this cost savings estimate into two sections; GPS RTK versus Total Station/Level and NRTK versus RTK. To effectively calculate an estimated cost savings, some parameters needed to be set up. For this estimate, an average, fictional, three-mile-long project that will take two and a half years to complete was used.

Using GPS to Locate Materials, FIATECH, University of Texas at Austin, 2004, presentation slides.

Powerpoint slideshow presented to FIATECH from KBR, Trimble Technologies, Data Scan, University of Texas, and FIATECH Smart Chips Project, includes good images of ruggedized HHC and GPS backpacks.

"Using Handheld Technology to Improve Student Learning," In *Phase II*, 2005.

The objective of the project was to provide training to school superintendents and administrators to use handheld technology and other skills to gather data from classroom observations related to teaching and learning practices.

The Visual Method to Develop a Project Schedule: Visual Project Scheduler Overview, n.d. [Online]. Available: http://www.visualengineering.com/EMISScheduling.html [accessed May 18, 2006].

An intuitive 4-dimensional computer-aided design (4D CAD)-based approach to developing a project schedule is now available. Now you can visually create project schedules using 2D or 3D models. Create schedules by selecting objects and creating activities in a 3D environment. Graphic visualization provides an enhanced opportunity for review, comment, and plan projects.

Visualization Symposium—Program Overview, Transportation Research Board, National Research Council, Washington, D.C., 2002 [Online]. Available: http://www.trbvis.org/default.aspx.

TRB Task Force on Visualization in Transportation (ABJ95T) announces its Preliminary Program Overview for the 2006 International Visualization in Transportation Symposium and Workshop. The focus of this event is to (through presentations and interactive panel sessions) better understand the spectrum of tangible, measurable benefits associated with their use across all modes of transportation and throughout the entire project development process.

Wailgum, T., "Why Wal-Mart's Suppliers Won't Make the Jan. 1 Deadline for RFID Tagging," *CIO Magazine*, Nov. 15, 2004.

Ward, M.J., A. Thorpe, A.D.F. Price, and C. Wren, "Mobile Wireless Data Capture for Piling Works," *Computer-Aided Civil & Infrastructure Engineering*, Vol. 18, No. 4, 2003, pp. 299–312.

Wasson, C., "Entering the Third Dimension: The Proper Care and Feeding of Emerging Technologies," *Grading & Excavation Contractor*, Sep./Oct. 2004.

There is a huge monetary payoff involved in the effective use of new 3D GPS surveying and machine-control technology, say experts. For that reason alone, its proliferation will increase rapidly, and barriers to its use will continue to topple.

Wilson, B., "Mississippi Moxy," *Roads & Bridges*, 2006.

Hurricane Katrina struck the Mississippi and Louisiana coastline on August 29, 2005. More than 100 days later, the Mississippi DOT had completed two major emergency bridge repair projects. The DOT allowed the use of IntelliRock concrete maturity, an in situ method of estimating the early strength in concrete on the I-10 bridge project as well as some previous paving projects. In the interim, the materials division instituted a process to publish a concrete maturity specification.

Wood, C.R. and M.W. Alvarez, *Emerging Construction Technologies: A FIATECH Catalogue*, National Institute of Standards and Technology, Gaithersburg, Md., 2005.

WordNet(r) 2.0. Princeton University, Princeton, N.J., 2003.

Yerrapathruni, S., J.I. Messner, A.J. Baratta, and M.J. Horman, "Using 4D CAD and Immersive Virtual Environments to Improve Construction Planning," Presented at CONVR 2003, Virginia Polytechnic Institute and State University, Blacksburg, Sep. 24–26, 2003.

This study is an investigation of the feasibility of using an immersive, 3D virtual environment to view and generate 4D models to improve the construction project planning process. A group of construction professionals interactively reviewed and generated a construction plan for a portion of a nuclear power plant project in an Immersive Virtual Environment (IVE). By reviewing their schedules in the IVE, the construction professionals were able to readily identify design, constructability, sequencing, and interdisciplinary interfacing issues. By interactively generating the construction schedule in the virtual environment, the professionals developed a plan that resulted in a 28% savings when compared with their original schedule. A process model for developing construction plans within an IVE is presented.

Zimmerman, C.A., J.L. Campbell, and C. Cluett, *NCHRP Synthesis of Highway Practice 296*: *Impact of New Information and Communication Technologies on Transportation Agencies*, Transportation Research Board, National Research Council, Washington, D.C., 2001, 57 pp.

The objective of this synthesis was to examine the impacts that information and communication (I/C) technologies are having on transportation agencies and to gather data to understand how agencies are dealing with those impacts. Although I/C encompasses a broad range of technologies, for the purposes of this study, four areas were examined: (1) intelligent transportation systems, (2) communication technology, (3) software tools, and (4) remote work arrangements.

APPENDIX G

Website URLs

GPS

Trimble home	http://www.trimble.com/
OPUS—What Is OPUS?	http://www.ngs.noaa.gov/OPUS/What_is_OPUS.html
UDOT–GPS information	http://www.udot.utah.gov/ets/GPS/default.htm
Howstuffworks: "How GPS Receivers Work"	http://www.howstuffworks.com/gps.htm
Autonomous GPS	http://www.agtek.com/autogps.shtm
GPS World—Home page	http://www.gpsworld.com/gpsworld/
Spectra Integrated Systems home	http://www.spectra-is.com/spectrais.htm
Trimble SiteVision 5	http://www.embeddedstar.com/press/content/2003/5/embedded8685.html
Precision Laser—GPS Trimble	http://www.laserinst.com/gps_trimble.html
Trimble home	http://www.trimble.com/index.aspx
Home—Point of Beginning	http://www.pobonline.com/
Take-off Professionals	http://www.takeoffpros.com/
Earthwork Service	http://www.earthworkservices.com/
UNIT 39—The TIN Model	http://www.geog.ubc.ca/courses/klink/gis.notes/ncgia/u39.html
Digital Terrain Modeling	http://www.geog.ubc.ca/courses/geog516/notes/dtm.html
DEMs	http://boris.qub.ac.uk/shane/arc/step3.html
Triangulated Irregular Network—Wikipedia	http://en.wikipedia.org/wiki/Triangulated_irregular_network
Triangulated Irregular Network—(GIS)	http://en.mimi.hu/gis/triangulated_irregular_network.html
Trimble—SPS750 and SPS850 Modular GPS	http://www.trimble.com/con_sps750_850.shtml
Trimble Productivity—Products	http://www.trimble-productivity.co.uk/productpage/index.cfm
Topcon Positioning Systems, Inc.	http://www.topconpositioning.com/index.html/session_id/94aa1aeeacb14c96e04a13dd06bacc8e/screen/tps_home_page/category_id/0
GPS World—Home page	http://www.gpsworld.com/gpsworld/
Accord's GPS Signal TapL2C	http://www.accord-products.com/gpsl2csignaltap.htm
L2C GPS GPS Review	http://www.gpsreview.net/l2c-gps/
GIS.com—Your Internet guide to GIS	http://www.gis.com/index.html
Open Geospatial Consortium, Inc.	http://www.opengeospatial.org/
GIS, CAD, GPS, mobile industry maps, news	http://www.geocomm.com/
RIDOT Survey	http://www.dot.state.ri.us/projects/survey/cors.html
National Consortium on Remote Sensing	http://www.ncgia.ucsb.edu/ncrst/research/projects/first.html
National Consortium on Remote Sensing in Transportation	http://www.ncgia.ucsb.edu/ncrst/research/projects/
National Consortium on Remote Sensing in Transportation	http://www.ncgia.ucsb.edu/ncrst/
Mn/DOT's GIS Statewide Base Map	http://ntl.bts.gov/DOCS/gis.html
U.S. Coast Guard Navigation Center	http://www.navcen.uscg.gov/
Dossier on GPS—Galileo	http://www.useu.be/Galileo/
Galileo GPS system hacked at Cornell	http://www.engadget.com/2006/07/13/galileo-gps-system-hacked-at-cornell/
Kentucky Transportation Cabinet	http://www.kytc.state.ky.us/design/survey/survey.asp
Global positioning system—Wikipedia	http://en.wikipedia.org/wiki/GPS
Bentley Systems, Inc.	http://www.bentley.com/en-us/
McAninch Construction	http://www.mcaninchcorp.com/

4D CAD

References/Standards

GSA—CAD Standards	http://www.gsa.gov/Portal/gsa/ep/channelView.do?pageTypeId=8195&channelPage=%252Fep%252Fchannel%252FgsaOverview.jsp&channelId=-12935
aecXML and Industry Foundation Classes	http://www.cadinfo.net/editorial/aecxml.htm
International Alliance for Interoperability	http://www.iai-na.org/technical/faqs.php
Start Page of IFC2x3 final documentation	http://www.iai-international.org/Model/R2x3_final/index.htm
Project Extranets	https://tsc.wes.army.mil/symposium/2004/TuesdayCDesignDel_Graves_files/frame.htm
Computer Integrated Building Processes	http://cic.nist.gov/
NavisWorks 3D Design File Formats	http://www.s2solutions.biz/formats.htm

Services

Visual Engineering	http://www.visual-engineering.com/

Products

Balfour Technologies—Home	http://www.bal4.com/
Bentley/Bentley Navigator	http://www.bentley.com/en-US/Products/Bentley+Navigator/Overview.htm?market=Building
CP: ConstrucSim Suite	http://www.commonpointinc.com/products/constructsim.asp
Bentley/4D Select	http://www.bentley.com/en-US/Community/Bentley+Partner+Program/Partner+Index/Building/4DSelect.htm
ArchVision home page	http://www.archvision.com/
CP: Common Point Inc.	http://www.commonpointinc.com/
Trelligence Affinity—Software for Architectural Programming and Schematic Design	http://trelligence.com/
4D CAD Research/Papers and Presentation	http://4d-server.stanford.edu/publications/4dDataBase.php
4D_Tutorials	http://laci.lcc.gatech.edu/4d/tutorials.phpes0607.pdf (application/pdf Object)

3D Products

Bentley/Bentley Navigator	http://www.bentley.com/en-US/Products/Bentley+Navigator/Overview.htm?market=Building
CSA—Construction System Associates	http://www.csaatl.com/
National CAD Standard official site	http://www.nationalcadstandard.org/
Bentley/DeskWare Products GmbH	http://www.bentley.com/en-US/Community/Bentley+Partner+Program/Partner+Index/Building/DeskWare.htm
Bentley/Riegl USA, Inc.	http://www.bentley.com/en-US/Community/Bentley+Partner+Program/Partner+Index/Civil/RieglUSA.htm
Bentley/ArchVision, Inc.	http://www.bentley.com/en-US/Community/Bentley+Partner+Program/Partner+Index/Building/ArchVision.htm
Adams:Kinkade—Home	http://www.invizn.com/index.html
Intergraph Process, Power & Marine	http://ppm.intergraph.com/smartplant/3d/
Visual Engineering	http://www.visual-engineering.com/
Carnegie Mellon Press Release: June 13	http://www.cmu.edu/PR/releases06/060613_3d.html
Feasibility Study of 4D CAD	http://www.pubs.asce.org/WWWdisplay.cgi?0003049
Realtime 4D CAD = RFID for project program	http://www.pubs.asce.org/WWWdisplay.cgi?0520032
Works : Paper w78-1997-23:Productivity	http://itc.scix.net/data/works/robots/w78-1997-23.htm
4D CAD Research/home	http://www.stanford.edu/group/4D/index.shtml http://www.stanford.edu/group/4D/project http://www.stanford.edu/group/4D/projects/bonsang/bonsang.htm
John Messner—4D CAD and Virtual Reality	http://www.arche.psu.edu/faculty/JMessner/Research%20Topics/4D_VR.htm
CIFE homepage	http://www.stanford.edu/group/CIFE/
The International Centre for Facilities	http://www.icf-cebe.com/
MIT Consulting: ConstructSim—Project	http://www.mitcg.com/constructsim.html
CSA—Construction System Associates	http://www.csaatl.com/
Distributed Virtual Reality	http://www.sv.vt.edu/future/vt-cave/apps/CatDistVR/DVR.html
Modelling (modeling)	http://www.insead.fr/CALT/Encyclopedia/ComputerSciences/System/modeling.htm
ProjNet: Public user	https://www.projnet.org/ProjNet/binKornHome/index.cfm?strKornCob=DrCkSubscription
MIT OpenCourseWare/Architecture/4.17	http://ocw.mit.edu/OcwWeb/Architecture/4-173Spring2004/CourseHome/index.htm
Bentley/Overview	http://www.bentley.com/en-US/Community/Bentley+Partner+Program/Partner+Index/
4D-Select	http://www.4dselect.be/
JetStream from NavisWorks	http://www.navisworks.com/
Computer-aided design—Wikipedia	http://en.wikipedia.org/wiki/Computer-aided_design#Software_applications
AECbytes: Analysis, research, and review	http://www.aecbytes.com/index.html
D-studio innovative IC—Technology	http://www.dstudio.be/index.php
Vineet R. Kamat, Ph.D.—Publications	http://pathfinder.engin.umich.edu/publications.htm

VR Products

Bentley/ArchVision, Inc.	http://www.bentley.com/en-S/Community/Bentley+Partner+Program/Partner+Index/Building/ArchVision.htm
Bentley/CAD & OFFICE AB	http://www.bentley.com/en-US/Community/Bentley+Partner+Program/Partner+Index/Building/CADOFFICE.htm
Intergraph Process, Power, & Marine	http://ppo.intergraph.com/visualization/
Screampoint LLC—5D Systems for Real Estate	http://www.screampoint.com/v2/index.htm
4D Visualization tools and vendors	http://www.construction.com/NewsCenter/it/features/01-20010723.asp
Introduction—4D CAD developer reference	http://www.microbizz.nl/caddocs/Introduction.html#Introduction
4D CAD research/research projects	http://www.stanford.edu/group/4D/projects/calvin/Seed_02-03.shtml
4D CAD research/research issues	http://www.stanford.edu/group/4D/issues/wishlist.shtml
Dallas High Five Interchange web cam	http://www.highfivecam.com/
The Transportation Planning Capacity	http://www.planning.dot.gov/Pitool/4c-f.asp
VectorWorks 12—CAD Software for the Smart-Sized Company	http://www.nemetschek.net/
Transportation Research Board for Visualization—Home	http://www.trbvis.org/

CONC

TRB Research in Progress > Browse project	http://rip.trb.org/browse/dproject.asp?n=9969
WAKE, Inc: Radio Frequency Identification	http://www.wakeinc.com/pages/RFID.html
intelliRock—Concrete maturity and concrete temperature profiling	http://www.engius.com/products/intellirock.html
Engius—Construction Technologies	http://www.engius.com/index.html

Handheld Computers

Handheld device—Wikipedia	http://en.wikipedia.org/wiki/Handheld_computer
PDAStreet—The PDA Network for Handheld Computers, Handheld Software	http://www.pdastreet.com/
oqo: Hardware: overview	http://www.oqo.com/hardware/basics/
Chronology of Handheld Computers	http://www.islandnet.com/~kpolsson/handheld/
Handheld computer UK computing guide	http://www.bundle247.co.uk/handheld-computer.html
Mobile solutions for facilities management	http://www.mobiledataforce.com/
RFID handheld readers from Symbol Technologies	http://www.symbol.com/category.php?category=727
Information mobility	http://ctca.unb.ca/CTCA/webfiles/online%20files/handheldcomputers.htm
AASHTO—AASHTOWare—FieldManager	http://aashtoware.org/?siteid=28&pageid=100
Trns•port System Architecture—Home	http://www.cloverleaf.net/sys_arch/
PCI Group—Construction project management	http://www.pcigrp.com/software/appia-fieldmanager-sr.htm
Campus Services: special projects: fall	http://www.its.uiowa.edu/cs/sp/pda/ExecutiveSummaryReportFall2001.html
Symbol Technologies corporate home page	http://www.symbol.com/
Accela, Inc./wireless	http://www.accela.com/products/landmgt_wire.asp
Nokia	http://www.nokia.com/staycurrent/
Symbol Technologies corporate home page	http://www.symbol.com/index.php
Personal computers and peripherals information	http://www.thezoomlist.com/computer_mfg/personal_computers_peripherals/handheld_computers.htm
Pocket PC magazine	http://www.pocketpcmag.com/_top/
Symbian OS home page	http://www.symbian.com/symbianos/index.html
Palm OS powers 40 million handhelds	http://www.palmsource.com/palmos/
Windows Mobile 5.0 smartphones and Pocket PC software	http://www.microsoft.com/windowsmobile/5/default.mspx
Software—OESF	http://www.oesf.org/index.php?title=Software#Where_can_I_download_software_.28free_or_otherwise.29_for_the_Zaurus.3F
Pen Computing Magazine: source for table	http://www.pencomputing.com/index.html
Rugged PC Review.com—Ruggedness Computing Industry Leaders	http://www.ruggedpcreview.com/2_leaders.html
Rugged PC Review.com—Handhelds and PDA	http://www.ruggedpcreview.com/2_handhelds.html
Pen Computing Magazine: 2005 Editor's Choice	http://pencomputing.com/editors_choice_2005/pdas.html
LXE's Mobile Computing Solutions, wireless computers	http://www.lxe.com/us/
Simputer™: welcome	http://www.simputer.org/simputer/
Amida Simputer: Full-featured handheld computer for individuals	http://www.amidasimputer.com/
MIT Media Lab and $100 Laptop	http://laptop.media.mit.edu/
Sharp Zaurus handheld PDA at sharpUSA.com	http://www.sharpusa.com/products/TypeLanding/0,1056,112,00.html
Zaurus Software Index	http://killefiz.de/zaurus/
IP Ratings Explained Ingress Protection	http://www.protectingpeople.co.uk/fire_tech/ip_explained.htm
IP—Ingress Protection Ratings	http://www.engineeringtoolbox.com/ip-ingress-protection-d_452.html
UL/environmental ratings for enclosure	http://www.ul.com/hazloc/ref/ingress.htm

NEMA protection rating information IP	http://www.appmeas.co.uk/techie2.html
IEC—International Electrotechnical Commission	http://www.iec.ch/
Pocket PC magazine	http://www.pocketpcmag.com/default.asp
Negroponte details specs on planned $100 laptop	http://www.engadget.com/2005/09/28/negroponte-details-specs-on-planned-100-laptop/
First Look: Sony Vaio UX180P Micro PC	http://www.mobiletechreview.com/ubbthreads/showflat.php?Board=news&Number=24461
DualCor Technologies, Inc.—Enabling Technologies for Mobility Solutions	http://www.dualcor.com/

WebCam

Welcome to VisualAsBuilts.com	http://www.visualasbuilts.com/
HKstudios Remote Project Monitoring	http://www.hk-studios.com/rpm.htm
Ahearn Holtzman Remote Project Monitoring	http://www.ahearnholtzman.com/ah_rpm.asp
OxBlue, Inc.—Construction webcams	http://oxblue.com/news/
OxBlue Corporation	http://oxblue.com/win/?siteID=fb2f517fbfb69d9aa713fdc2d5640edf
Walton Construction Company, Inc.	http://oxblue.com/client/waltoncci/regency/
Remote Video Monitoring	http://coastal.er.usgs.gov/rvm/
Matrix Center for Remote Viewing and Advanced Mind Technology	http://www.matrixaccess.com/index.html
Privat-Webcam dot com/TOP 100/webcams 1–10	http://www.private-webcam.com/webcams.php4
Open Directory—Computers: Internet:	http://dmoz.org/Computers/Internet/On_the_Web/Webcams/Software/
WSDOT—SR 16, Tacoma Narrows Bridge project	http://www.wsdot.wa.gov/projects/sr16narrowsbridge/webcams/camera.cfm?module=easttower.cfm
Project webcams	http://www.rdolson.com/webcams_index.htm
Hawkins Construction Company	http://www.hawkins1.com/webcams.html
New State Library of Queensland project	http://map.slq.qld.gov.au/cgi-bin/calendar.pl
WebCams for the project—www.rtcwashoe.com	http://www.rtcwashoe.com/streets/projects/fy03/395clearacre/webcams/
I86 Home	http://www.dot.state.ny.us/reg/r6/i86_project/i86home.html
Camvista.net—Construction webcams	http://www.camvista.net/
Construction webcams	http://www.contractorcity.com/modules.php?name=ConstructionWebcams
Camera with Built-In Thermostat Heater 9-24 mm EZ300/N-2	http://www.smarthome.com/7662.html
Remote Construction Monitoring System	http://www.pathnet.org/sp.asp?id=7525
REMONTECH—Remote Monitoring Technological	http://www.remontech.com/
Web camera images at ERDC	https://webcam.crrel.usace.army.mil/
Construction webcams—Internet construction	http://www.webcamstore.com/consumer/applications/construction.php
Faculty of Management Building Construction	http://www.cs.dal.ca/cam/construction1.shtml
Falkirk Wheel and Millennium Link Resource	http://www.gentles.info/link/Main_index.htm
EarthCam—Webcam network	http://www.earthcam.com/index.php
REMONTECH—Remote Monitoring Technological Photo-Net 2	http://www.remontech.com/photonet2.shtml
Daniel G. Aliaga home page	http://www.cs.purdue.edu/homes/aliaga/
iBEAM construction cameras/home/1-80	http://www.ibeamsystems.com/
StarDot Technologies—Network cameras and video servers	http://www.stardot-tech.com/
Contractor employee time clock	http://www.abouttimetech.com/index.htm
TRB Research in Progress >	http://rip.trb.org/browse/dproject.asp?n=11621
NCHRP project	http://www4.nas.edu/trb/synthsis.nsf/All+Projects/Synthesis+37-06
Emerging Construction Technologies	http://www.new-technologies.org/ECT/Other/other.htm
Burcu Akinci's home page	http://www.ce.cmu.edu/~bakinci/
AASHTO—AASHTO Technology Implementation	http://www.aashtotig.org/?siteid=57
Bentley/ProjectWise	http://www.bentley.com/en-US/Products/ProjectWise/
Kentucky Transportation Cabinet	http://transportation.ky.gov/highways/
Accelerated Construction Technology Transfer	http://199.79.179.101/construction/accelerated/index.cfm

Terrain

3D Studio Tutorial—Creating terrain objects	http://www.cadtutor.net/dd/studio/terrain/terrain.html
Bentley/PowerCivil Resource Center	http://www.bentley.com/en-US/Products/Bentley+PowerCivil/ResourceCenter.htm#screenshots
Arc GIS Tutorial	http://people.revoledu.com/kardi/tutorial/GIS/TIN%20Model.htm
Unit 056—The TIN Model	http://www.ncgia.ucsb.edu/giscc/units/u056/
Triangulated Irregular Network	http://www.ian-ko.com/resources/triangulated_irregular_network.htm
403.pdf (application/pdf object)	http://www.isprs.org/istanbul2004/comm3/papers/403.pdf
Changes in XYZ Export in TIN MODEL	http://www.hypack.com/newsletter/7_02/Pat_2.htm
automatic_building_extrusion_tin_lidar.pdf	http://www.voronoi.com/pdfs/2005-2010/automatic_building_extrusion_tin_lidar.pdf

Abbreviations used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation