A2F09: Committee on Application of Emerging Technologies
Chairman: Carl Haas

Emerging Technologies for Transportation Construction

RICHARD GRIFFIN, *Colorado Department of Transportation*
RONIE NAVON, *Technion—Israel Institute of Technology*
AVIVA BRECHER, *U.S. Department of Transportation/Research and Special Programs Administration, Volpe Research Center*
DICK LIVINGSTON, *Turner Fairbank Highway Research Center, Federal Highway Administration*
CARL HAAS, *University of Texas–Austin*
DARCY BULLOCK, *Purdue University*

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 the equivalent work can be performed with fewer workers. The automation is likely to prove more reliable, efficient, and cost-effective as well.

ENVIRONMENTAL AND SAFETY CONCERNS

Concerns related to the environment and worker safety will probably intensify. Construction contractors will increasingly be called upon to use innovative construction materials and techniques that have less environmental impact and provide safer working conditions.

An important area for research and development (R&D) in highway worker safety will be the development of healthier and safer materials, procedures, and equipment for construction and resurfacing. The elimination of toxic paints, sprays, coatings, dust, noise and vibration, radioactive materials, carcinogenic tars and oils, and the like will become an important aspect of transportation construction. Use of recyclable construction materials and cold-treatment surface applications will also increase. Characteristic of these developments is the emerging nondestructive test and monitoring technology exemplified by the Federal Highway Administration’s (FHWA) recent development and field validation of a new, safe (not radioactive), and easily portable soil stiffness gauge based on acoustic and seismic sounding.

TECHNOLOGIES FOR MONITORING, GUIDING, AND COORDINATING CONSTRUCTION EQUIPMENT AND ROBOTS

Construction equipment and robots, or automated and preprogrammed machinery, will incorporate advanced technologies for guidance, monitoring, and control. These technologies were developed for application in such areas as aeronautic navigation, mobile robot navigation, and geodesy. Included among these technologies are inertial navigation systems, active beacon navigation systems, the Global Positioning System (GPS), ground-based radio frequency systems, ultrasonic and optical systems, and radio frequency identification systems.

Inertial Navigation Systems

The basic inertial navigation system consists of gyroscopes, accelerometers, a navigation computer, and a clock. Gyroscopes sense angular rate and are used to determine the orientation of an object. Accelerometers sense a linear change in rate (acceleration) along a given axis. In a typical inertial navigation system, there are three mutually orthogonal gyroscopes and three mutually orthogonal accelerometers. This accelerometer configuration results in three orthogonal acceleration components that can be vectorially summed.

Combining the gyro-sensed orientation information with the summed accelerometer outputs yields the total acceleration in three-dimensional space. At each time-step of the system's clock, the navigation computer time-integrates this quantity once to get the body's velocity vector, which is then time-integrated, yielding the position vector. These steps are continuously iterated throughout the navigation process.

The main advantage of an inertial navigation system is that it is self-contained, which means no external motion information is needed (1). As a result, the “noise” and error sources of an inertial navigation system are independent of external sources. Additional benefits of inertial navigation systems are that they are nonradiating—an important factor if they are to be used in a construction environment—and they cannot be jammed. Presently, the main disadvantage of an inertial navigation system is that it suffers from a phenomenon termed “drifting”; as a result, relatively accurate systems (about 0.1 percent of distance traveled) are still expensive. It is expected that this drawback will eventually diminish.

Active Beacon Systems

Active beacon systems, including GPS, used for surveying both before and after the design work, will speed project layout and reduce errors. Using active beacon systems to guide and control construction equipment directly will reduce the need for construction surveying. One of the significant challenges to deploying active beacon systems for construction automation will be horizontal, vertical, and longitudinal datums. The issue here is that very few (if any) as-built surveys of existing roadway infrastructure have the relative accuracy necessary for implementing autonomous construction equipment in a systematic manner. However, once a commitment has been made to obtaining (and maintaining) these surveys, it should be possible to download plans for superelevation, guardrail placement, and perhaps even pavement striping to autonomous or semiautonomous equipment for execution.

Active beacon systems are based on three or more transmitters at known locations and one receiver on a mobile unit whose location is to be determined. There may also be only one transmitter on the mobile unit and three or more receivers at the known locations. Active beacon systems can operate on either of two principles: trilateration or triangulation. In trilateration, the position of the mobile unit is determined on the basis of measured distance to known beacon sources. Using time-of-flight information, the system computes the distances between the transmitter(s) and the receiver(s). These distances are used to compute the location of the mobile unit. In triangulation, a rotating sensor on the mobile unit registers the angles between a longitudinal axis and the beacons at the fixed locations. The system computes the coordinates of the mobile unit on the basis of these angles.

Global Positioning System

GPS consists of a network of 24 satellites orbiting about 19,000 km from earth. Two pseudomicrowave signals, carrying encoded data, are transmitted from the satellites. The position of an object is calculated using trilateration principles.

The normal accuracy of GPS equipment is 100 to 200 m. This accuracy can be increased tenfold, or even more, using differential GPS (DGPS). Such a system uses an additional receiver at a fixed, known location relatively close (within 10 km) to the receiver on the mobile unit. The additional receiver is subject to the same error effects when using the same reference satellites, thus making it possible to measure and correct the error. The main advantages of GPS or DGPS are declining cost, increasing accuracy, and the ability to be employed by multiple users—an important feature for monitoring construction equipment.

Ground-Based Radio Frequency Systems

Ground-based radio frequency systems are based on the same principles as GPS, with two exceptions: first, they use ground stations instead of satellites as the reference; second, they use a different transmitting frequency, although the position of an object is still calculated using trilateration principles. These systems are typically of two types (2):

- Active radar-like systems, which have several fixed stations, including a main station and substations. At predefined times, the main station transmits a coded signal, which includes the station's identification. When received by the substations, the signal activates each substation to send its own coded signal, which is received by mobile units. The locations of the mobile units are computed using trilateration. The number of fixed stations—at least four to provide a three-dimensional location—is determined according to coverage needs and the topography involved.
- Passive systems, whereby all the fixed stations are connected to a control center that activates them simultaneously. The signal is received by the mobile units and returned to the fixed stations. The time measurement and the location computations are performed by the control center.

The main advantages of radio frequency systems are that they can serve a large number of mobile units, can provide a desirable level of accuracy, can be relatively small, and are affordable. The major shortcoming of these systems is that those now commercially available still have problems related to electromagnetic shielding and reflection.

Ultrasonic and Optical Systems

These systems use ultrasonic or optical beams. One rotating transmitter-receiver is typically located on a mobile unit, whose location is to be determined, with three or more stationary reflectors being mounted at known locations (2). Ultrasonic trilateration systems are suitable for operation in relatively small, unobstructed work areas because of the short range of the ultrasound. Optical systems include a number of variations (3); among these are scanning detectors with fixed active beacon emitters, scanning emitters and detectors with passive retroreflective targets, scanning emitters and detectors with active transponder targets, and rotating emitters with fixed detector targets.

An example of the commercial use of an optical system for position location in the construction arena is CAPSY. This system can determine its own planar location in an area of 50 x 50 m with an accuracy of 3 mm. The system's current main use is for measurements for as-built drawings. CAPSY has also been used for controlling the location of materials on site (4).

Both ultrasonic and optical systems are accurate and lightweight and relatively inexpensive. One of their principal disadvantages is the need to maintain a clear line of sight between the beacon and the mobile unit. The systems are also affected by the presence of other objects or people in their vicinity and by changes in barometric pressure, temperature, and humidity.

Radio Frequency Identification Systems

Radio frequency identification is an auto-identification technology (5) involving the transfer of information via a tag or transponder that can be attached to almost any object. In a radio frequency identification system, an identification transponder sends and receives bidirectional radio signals to a reader. These signals are then sent to a host computer. Radio frequency identification has advantages over other auto-identification technologies, such as being able to perform in places where vision is blocked or where surfaces are dirty.

Several radio frequency identification applications have been developed for use in transportation, manufacturing, law enforcement, and agriculture. These applications involve reading the tag as an object passes a fixed scanner in order to record the movement of the object past the scanner, and writing information on the tag that can be retrieved later. Information is retrieved from tags (at a distance of up to 73 m) using a mobile scanner. Information gathering is thereby expedited, and misplaced objects can be located more easily because the operator does not have to go to the exact location of an object. These technologies also have potential application for manpower control (6) and for use of construction equipment and robots (7).

SMART STRUCTURES

Recent developments in fiber-optic detector technologies have enabled low-cost, long-term monitoring of strains, temperatures, and chemistry. As a result, it is now possible to build smart structures that can facilitate the achievement of quality in construction. During construction, fiber-optic strain gauge systems can be used to monitor prestress during and after casting of the structural members, as well as concrete temperature history and shrinkage in both precast and cast-in-place members. Once construction has been completed, the system can be used to measure deformations under load testing to verify design calculations. These fiber-optic systems can also remain in place to meet operational needs such as weigh-in-motion, incident detection, and overall structural health monitoring.

FHWA has developed a system using Bragg grating fiber-optic sensors. This technology is especially attractive because a large number of sensors can be placed on a single fiber, reducing both the physical space required for cabling and labor costs for installation. The sensors are also highly durable and are not subject to drift or electromagnetic interference. Prototype fiber-optic sensor systems consisting of up to 64 sensors have been embedded in several concrete bridges in the United States and abroad, and have performed well. The sensors can be embedded directly in the concrete or can be attached to reinforcements before the concrete is placed.

MODULAR CONSTRUCTION AND ADVANCED MATERIALS

Modular construction of roadways, bridges, and peripherals with advanced materials will be expanded in the next century to reduce cost and minimize traffic disruption through the rapid assembly of lighter, more durable components. Modular construction can take many forms, including prefabricated pavement components, bridge components, and foundations.

The most significant benefit of modular construction is shorter construction times, which reduce traffic disruption and exposure of workers and highway users to the safety hazards of construction zones. Additionally, quality can be improved and cost reduced when components are built in a factory instead of in a field setting. Advanced materials that cannot be adequately controlled in the field can be used or fabricated under controlled factory conditions. After partial curing or fabrication, the material or modules can be transported to the field for final assembly, installation, or curing.

Modular construction and the use of materials such as advanced composites, fiber-reinforced polymer, metal matrix composites, and even conventional materials (e.g., aluminum truss bridges) are complementary. The lighter weight and flexibility of form that characterize advanced materials make modular components feasible when conventional materials would not work. Conversely, modular construction allows factory forming of advanced materials, which generally require controlled conditions. Certain materials can be used in a factory environment but could not normally be handled in the field because of the inability to control the environment and the release of hazardous materials.

An intriguing example of modular construction is the Tech 21 fiberglass bridge built in Butler County, Ohio, in just 46 days (8). Partners on this project were the County Engineer, Dean Foster; Wright Laboratories Materials Directorate of Wright-Paterson Air Force Base; LBJ Engineers & Architects; and Martin Marietta Materials. Continuous E-glass fibers were used in a matrix of isopolyester resin for the beams and deck. The superstructure of the 24 ft wide by 33 ft long bridge weighs only 22,000 lb and has an asphalt-wearing surface. The experimental bridge is heavily instrumented, and a telecommunications link provides an instant warning if potentially fatal distresses are detected.

FOUR-DIMENSIONAL VISUALIZATION

Advanced space-based remote sensing and virtual-reality tools will enable four-dimensional visualization in near real time, allowing for better construction project planning, management, and documentation and the monitoring of environmental and traffic impacts. The merging of high-resolution space imagery with geographic information systems, terrain aerial photos, and demographic and other mapping databases offers great promise for enabling cost-effective land use and transportation planning by state, regional, and metropolitan planning organization planners, as well as by construction contractors.

Archived, near-real-time, and real-time satellite imagery, including color, infrared multispectral, and hyperspectral imagery, is becoming available in digitized and customized form. New virtual-reality tools will convert geographic data into virtual-reality objects. These tools will allow the overlay of road maps, infrared or multispectral digitized imagery, and U.S. Geological Survey elevation topographic maps onto “flyover" terrain for virtual travel. This technology, coupled with a near-real-time or real-time remote imaging system, could become a tool for highway design, construction, or inspection. Construction project managers could “fly over” a project to verify and document project progress and compliance with specifications. Traffic congestion created by the project and compliance with environmental regulations could be monitored. The project engineer could verify and document lane closure activities for compliance with rush-hour requirements or assessment of lane-rental charges. These technologies could also be used to verify compliance with roller timing and pattern requirements for asphalt paving.

TOTAL ELECTRONIC INTEGRATION

The new millennium will see total electronic integration of the entire process of transportation system construction, linking all the steps in the process together electronically. Site surveying, design, equipment and robotic instructions, quality assurance/quality control, reporting, payments, and as-built drawings will all be totally integrated. The result will be an environment in which information is passed electronically from step to step, with no paper handling involved. Direct linking of instructions for construction equipment and robots to the electronic design plans will minimize errors, improve quality, and simplify robotic programming.

Computers are playing an increasing role in the construction process, especially in the design phase. Designers still use computer-aided design systems as drafting tools, mimicking manual drafting to a large extent. Automatic integration of design and construction is not possible without a radical change in this procedure. Several models using a different approach to design that allows automatic extraction of construction-related data from the design database have been developed (9–11). These models and the systems used for their implementation help improve the construction process in several ways:

- They reduce the number of steps involving manual data processing, thereby reducing many error sources and the associated economic implications.
- They automate and improve the design process, thereby lowering design costs and improving the design product.
- They increase compatibility of design and improve communication. Eventually, automated collection of data on pavement loading geometry and distresses may be integrated electronically into the design.

CONCLUSION

The advanced technologies and innovative methods discussed here, as well as other concepts yet to be conceived, will be needed for transportation infrastructure construction in the new millennium to meet the public’s demand for high-quality and convenient transportation. Innovative and more flexible contracting practices, such as design–build, lane rental, life-cycle warranties, and bonuses for early completion, will increasingly be used. These practices will encourage and enable contractors to make full use of the new technologies and complete work quickly with the minimum disruption to traffic, while incorporating quality that will ensure long-lasting, low-maintenance facilities.

REFERENCES

1. Parish, D., and R. Grabbe. Robust Exterior Autonomous Navigation. Proceedings of the 1993 SPIE Conference on Mobile Robots. Boston, Mass., 1993, pp. 280–291.
2. Borensyein, J., H. R. Everett, and L. Feng. Where Am I? Sensors and Methods for Autonomous Mobile Robot Localization. Technical Report UM-MEAM-94-21. University of Michigan, 1994.
3. Everett, H. R. Sensors for Mobile Robots: Theory and Application. Wellesley, Mass.: A. K. Peters Ltd., 1995.

4. Tommelein, I. D. Materials Handling and Site Layout Control. Proceedings of the 11th International Symposium on Automation and Robotics in Construction. Brighton, U.K., 1994, pp. 297–304.
5. Jaselskis, E. J., M. R Anderson, C. T. Jahren, Y. Rodrigues, and S. Njos. Radio-Frequency Identification Applications in Construction Industry. Journal of Construction Engineering and Management—ASCE, 121(2):189-196, 1995.
6. Navon, R., and E. Goldschmidt. Automated Data Acquisition for On-Site Control. To be published in Proceedings of the 16th International Symposium on Automation and Robotics in Construction. Madrid, Spain, 1999.
7. Navon, R., and E. Goldschmidt. Labor Utilization Control. To be published in the Proceedings of the Joint Triennial Symposium, Customer Satisfaction: A Focus for Research and Practice. South Africa, 1999.
8. Weir, D. A. Fiberglass Bridge for the 21st Century. Ohio LTAP Quarterly, 15(1), Ohio State University, 1999.
9. Navon, R., Y. Rubinovitz, and M. Coffler. RCCS: Rebar CAD/CAM System. Microcomputers in Civil Engineering, 10(6):385-400, 1995.
10. Navon, R., Y. Rubinovitz, and M. Coffler. Fully Automated Rebar CAD/CAM System: Economic Evaluation and Field Implementation. Journal of Construction Engineering and Management—ASCE, 122(2):101-108, 1996.
11. Navon, R. COCSY II: CAD and Construction (CAM) Integration for On-Site Robotics and Construction Management. Journal of Computing in Civil Engineering—ASCE, 11(1):17-25, 1997.