NISTIR 5667 V1

A Study of Potential Applications of Automation and Robotics Technology in Construction, Maintenance and Operation of Highway Systems: A Final Report

Ernest Kent
Intelligent Systems Division

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology
Bldg. 220 Rm. B124
Gaithersburg, MD 20899

NIST

NISTIR 5667 V1

A Study of Potential Applications of Automation and Robotics Technology in Construction, Maintenance and Operation of Highway Systems: A Final Report

Ernest Kent
Intelligent Systems Division

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology
Bldg. 220 Rm. B124
Gaithersburg, MD 20899

June 1995

U.S. DEPARTMENT OF COMMERCE
Ronald H. Brown, Secretary

TECHNOLOGY ADMINISTRATION
Mary L. Good, Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Arati Prabhakar, Director

FINAL REPORT

VOLUME: 1

To:
FEDERAL HIGHWAY ADMINISTRATION

Prepared by:

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Dr. Ernest Kent

TABLE OF CONTENTS

Abstract.

The National Institute of Standards and Technology, at the request of the Federal Highway Administration, has conducted a study of potential applications of automation and robotics technology in construction, maintenance, and operation of highway systems. The study included a workshop exploring industry perceptions of needs and barriers to adoption, a workshop and a literature search to assess current state of the art practices and trends, and site visits by automation experts to typical highway worksites. Potential technology opportunities were highlighted for short, medium, and long-term efforts in a matrix of intersections between common highway jobs and areas of current technological thrust. From among the opportunities identified, six potential research areas were developed as specific proposals, and subjected to life-cycle cost-benefits analysis. Four were projected to return significant savings by comparison with current practice. Of these, two were identified as also likely to return benefits of significant impact on total highway expenditures and the national economy due to their ability to leverage savings across large numbers of jobs or their effect on a large percentage of highway traffic.

SECTION: 1

ACKNOWLEDGMENTS

ACKNOWLEDGEMENTS

The efforts of many people in conducting this study, and of those who assisted in its preparation and execution are gratefully acknowledged.

We would like to particularly thank **Mr. Thomas Pasko**, Director, Office of Advanced Research, FHWA for conceiving and sponsoring the entire project, and **Dr. Charles Woo**, Research Highway Engineer, FHWA for his invaluable aid and guidance in every phase of its conduct.

The following persons deserve special recognition for their service:

THE STUDY PANEL:

Dr. James Albus, Division Chief, Robot Systems Division, NIST

Dr. Leonhard Bernold, Associate Professor, Civil Engineering, Director, Construction, Automation and Robotics Laboratory, North Carolina State University

Dr. Kerien Fitzpatrick, Project Scientist, Field Robotics Center, Carnegie Mellon University

Mr. Kenneth Goodwin, Group Leader, Performance Measure, NIST

Dr. Avi Kak, Professor, Electrical Engineering, Robot Vision Laboratory, Purdue University

Dr. Ernest Kent, Chief Scientist, Robot Systems Division, NIST

Dr. Ronald Lumia, Group Leader, Intelligent Controls, Robot Systems Division, NIST

Dr. Arthur Sanderson, Professor - Chairman of Electrical, Computer Systems Engineering Department, Rensselaer Polytechnic Institute

SITE VISIT HOSTS:

Mr. John Mack, Urban Engineer, FHWA Texas Division

Ms. Lori Kennedy, District Engineer, FHWA Georgia Division

Dr. Thomas West, California Department of Transportation

FHWA ADVISORS:

Dr. James Wentworth, Supervisory Research Highway Engineer, FHWA

Dr. Mort Oskard, Research Structural Engineer, FHWA

OTHER PARTICIPANTS AND CONTRIBUTORS:

Dr. Charles Nichols, Consultant, CERF

Dr. Ray Hariri, Program Manager, CERF

Dr. Robert Cromwell, Research Scientist, Robot Vision Laboratory, Purdue University

Mr. Robert Finklestein, President, Robotic Technology, Inc.

Ms. Leah Jollie, Secretary, Robot Systems Division, NIST

Mr. Jay Etris, Research Engineer, CERF

Dr. Basil Dendrou, Technical Director, Micro Engineering, Inc.

SECTION: 2

EXECUTIVE SUMMARY

Executive Summary.

The National Institute of Standards and Technology, at the request of the Federal Highway Administration, has conducted a study of potential applications of automation and robotics technology in construction, maintenance, and operation of highway systems. The study included a workshop exploring industry perceptions of needs and barriers to adoption, a workshop and a literature search to assess current state of the art practices and trends, and site visits by automation experts to typical highway worksites.

The first volume of this report contains an overview of the study and the methods employed, a summary of the principal results, several white papers examining selected topics of interest, and a bibliographic study. A second volume presents proposals for particular research possibilities developed by the study panel, and a life-cycle cost-benefits anlysis of the proposed research under the assumption the expected technological goals could be achieved. The third volume contains proceedings of workshops organized to educate the study panel with respect to the highway industry, and with respect to current state of the art. A final volume contains the set of final research proposals setting out specific studies with proposed delverables, support levels, and timetables. Additional documents and videotapes included in the various volumes are described in the summary of results.

The study was conducted by a group of automation and robotics experts from academia and government. Some of the panelists additionally had civil engineering backgrounds. The panel sought to gain an in-depth understanding of issues and needs in the highway industry through meetings and discussions with contractors, equipment manufacturers, materials suppliers, and state DOT engineers, and through site visits to highway construction and maintenance sites and highway operations facilities. During the site visits, the panelists also interviewed job-site supervisors and equipment operators, and other personnel. The panel evaluated the current state of relevant technology out of its own expertise, augmented by a search of the relevant literature and an invited workshop focused on current research in the field, sponsored jointly with the National Science Foundation.

From these resources, the panel identified a variety of highway industry op-

portunities for automation, and correlated these with research and development opportunities suggested by the current state of the art in automation and robotics. These potential areas of contact were organized into a matrix of research opportunities, which the panel then further classified in terms of its estimate of the potential for near-term, medium-term and long-term efforts to achieve the necesary research or development goals.

A principal goal of the study was to identify a selection of specific research proposals and to evaluate their potential benefit to problem areas of the highway industry. The panel selected six potential research programs for detailed evaluation. Specific research projects were defined, and the technical objectives sought were interpreted in terms of their perceived benefits for highway work. These proposals were submitted to the Civil Engineering Research Foundation (CERF) for a study of life-cycle cost-benefits, under the assumption that the technical objectives could be met. CERF performed the analysis with the assistance of a group of engineering professionals from State DOTs, industry, and academia. Qualitative and quantitative information was gathered and analysed, and costing was estimated for typical scenarios using current and proposed methods.

Four of the proposals were projected to provide significant economic improvements over current practice. Of these, two were judged capable of providing significant benefits to the national economy and traveling public at large by virtue of the leveraging effect of large-scale highway construction, maintenance, and operations issues on their estimated benefits. Some of the proposals were augmented, modified, or withdrawn following the cost-benefits analysis, and all those remaining were reformulated as specific programs of research in the form of proposals for research support, with specific timelines, efforts, deliverables, and support levels.

SECTION: 3

OVERVIEW OF THE STUDY

Overview Of The Study.

1 Origin.

The Office of Avanced Research of the United States Department of Transportation, Federal Highway Administration, under the direction of Mr. Thomas Pasko, has the mission "To plan, administer, conduct, and coordinate fundamental research and innovative adaptations for emerging and advanced technologies which have potential for long-range applications in the highway program." In pursuit of this mission, the Office of Advanced Research contracted with the Robot Systems Division of the National Institute of Standards and Technology to conduct a study of the potential applications of automation and robotics technologies to relevant problems in highway construction, maintenance, and operations which might be beneficially advanced by FHWA activities. The study was planned and coordinated by Dr. Charles Woo of FHWA, and carried out by personnel of NIST, together with consultants from the Civil Engineering Research Foundation, Robotic Technology, Inc., Carnegie Mellon University, Purdue University, Rensselaer Polytechnic Institute, and University of North Carolina State.

2 Rationale.

The nation's highways are a very major component of the national infrastructure. It is widely acknowledged that there is a developing general crisis in maintenance of the American civil infrastructure. Highways, bridges, sewers, railroads, harbors and public buildings built in the 1950s and 1960s are wearing out, while federal spending on infrastructure has fallen from roughly 5 percent of all U.S. budget outlays in the 1960s to less than 3 percent in the late 1980s. The results are starting to show. The U.S. Department of Transportation, for example, estimates that Americans spend more than 2 billion hours tied up in traffic on urban highways each year – delays that cost the nation $35 billion in lost interstate commerce.

Research by David Aschauer, a former senior economist at the Chicago Federal Reserve Bank, concludes that "there is a distinct positive relationship between infrastructure and productivity", and that "the drop-off in infrastructure spending is clearly a significant factor in the nation's sagging productivity growth." U.S. News and World Report says that "even conservative studies suggest that a one-time investment of $20 billion to improve roads, airports, and other core infrastructure would raise the output of the nation's businesses by $13 billion every year thereafter and ratchet up the productivity of existing assets."

Clearly a major new investment needs to be made in the American infrastructure. At issue, is how to make this investment pay the highest dividend in terms of increased productivity. There are enormous productivity benefits to be derived from the development of improved methods of civil construction to increase the efficiency and reduce the cost of the work required. The single greatest opportunity lies in adapting the principles of industrial automation to the field of civil construction. Successfuly accomplished, this would provide an enabling technology which could leverage the existing investment of the civil construction industry in machines and personnel, and could apply as beneficially to repair of existing infrastructure as to new construction. Because essentialy similar problems and procedures in highway construction and maintenance span enormous distances and vast amounts of invested capital, the nation's highway system presents a magnificent opportunity to approach these goals through the solution of a relatively restricted set of problems.

It is overly simplistic to conceive of this simply in terms of robotics applied to construction machinery; successful accomplishment requires the broad perspective of true automation. The lessons of industrial automation have taught us that robotics is successful only when combined with design for automation, automated planning, integrated materials flow, automated measurement and inspection, standard database and data exchange formats, and a variety of other technologies now emerging in the U.S., Europe, and Japan as necessary constituents of the automation process. Such a broad-spectrum approach to the automation of the highway construction industry can not only address the problem of the public cost of maintaining the American highway infrastructure, but can have beneficial impact on the American economy in many other ways as well.

3 General Economic Benefits.

Beyond the great benefit of reducing the cost of maintaining the public infrastructure, the following benefits may be expected from rapid application of automation to higway construction:

- Advances in automation for highway construction can revitalize the American highway construction industry and a host of derivative industries. Aided by advanced technology, these industries will not only become more profitable, but will also be more competitive in the global construction market.
- Jobs can be created. The evidence of automation in manufacturing shows that the ultimate result of improved efficiency through automation is to create new jobs, new industries, and higher-skilled jobs.
- Productivity can be increased significantly in a major section of the American economy, thereby contributing significant real growth in GNP.
- The market for high-technology automation services and equipment created by automation of the highway construction industry will provide a stimulus to lagging U.S. high-teghnology industries.

- The development of new generations of equipment for automated construction will support American export markets.

A major research initiative addressing these issues, as well as improved automated devices and processes, is required, and could quickly pay substantial dividends in improved efficiency and cost savings. However, the highway construction industry in the United States consists of many, non-vertically integrated components. Many of these are small sub-contractors. Others specialize in various kinds of equipment manufacture or materials handling. In such an environment, no single participant nor industry segment will have the opportunity or resources to develop the necessary technology. The Federal government, through its laboratories and its agencies for the regulation and oversight of civil construction, does have the necessary breadth of experience and skills to direct and support the development of this technology in the national interest. The Federal government, directly, and indirectly through subsidies to state and local governments, is also a major consumer of this industry's product. It is thus in a position to accelerate the adoption of new technologies by the industry. Given a problem of this scale, a coordinated program of research, having the necessary scale and breadth to address the issues cited, can only be mounted by a Federal research initiative, in cooperation with the relevant segments of the civil construction industry.

The first objective of such a program must be to identify and provide the range of technologies which must be brought together for a successful transition of the highway construction industry from its present status to that of a high-technology, automated industry. The second objective must be to ensure that the necessary standards and other requirements for integrating these technologies exist. The third objective must be to transfer this technology and its integration effectively into the industry. The present study attempts to begin this process by investigating the opportunities presented by the conjunction of current industrial automation technology with current highway construction and maintenance practices. It attempts to identify both targets of opportunity for immediate application of existing technology, and the most highly-leveraged opportunities for research which can extend that technology into the highway arena.

4 Technical Approach.

The current state of the art in robotics and automation has been driven to a very large degree by the requirements and environment of manufacturing applications. At the outset, it was recognized that there are many similarities between problems addressed by automation in factory-based manufacture, and activities common to highway construction, maintenance, and operation. Construction is a form of manufacture. In the instance of highways, maintenance as well is often similar to manufacture, since repair frequently requires that roadways and structures be essentially re-constructed. Additionaly, however, maintenance may require special procedures such as stripping of old paint, which present specialized problems. Operations, for example management of traffic around construction sites, can have underlying similarities to such traditional problems as managing manufacturing materials flow, but other issues such as trash collection appear novel.

Because of the structural similarity of construction equipment to much automated robotic equipment, it is initially tempting to suppose that the addition of robotic controls to such equipment in an attempt to convert the construction site to something similar to an automated factory might be a reasonable first approach. Several considerations argue against this. At the level of physical devices, the great difference between the highway-site problem and traditional automated manufacturing problems lies in the degree of structure that can be imposed on the environment. In the factory, the position and orientation of materials is easily constrained, the timing of parts presentation can be controlled, tolerances can be rigidly specified, and the completion-time of operations is invariant. These conditions are hardly ever found in the field.

The technical means to cope with these difficulties exist to greater or lesser degree in current robotics technology. What is required in principle to solve such problems is more elaborate sensing, e.g., machine vision, to ascertain the actual state of affairs, and more flexible and intelligent control systems to correct the devices' actions to compensate for variance in the situation. Unfortunately, these technologies, where they even exist with sufficient capability, are very costly. Real-time vision systems and computers capable of guiding flexible real-time behavior represent substantial investment. Additionally, devices which achieve such capability are typically not robust enough for daily field usage. On the other hand, at the organizational level, the problems of planning and scheduling, inventory control, task assignment, resource utilization, database management, and other tools of automation appear formally quite similar to those routinely encountered in factory automation, provided that the physical means exist to collect information and to project action based on decisions.

In light of these considerations, it was decided that the most reasonable technical objectives for the present study would be:

- To identify highway practices currently within the competence of available robotics technology, or reasonable extensions to that technology, in which current highway industry practice is especially costly or difficult, e.g., for reasons of safety or environmental considerations, and which would therefore represent a cost-effective target for even complex physical automation.

- To identify highway practices, e.g., some rebar placement and tying operations, in which the constraints on the environment can be made to approximate those existing in factory environments, and to seek means to apply factory-robotics technology to such situations in a manner that would be cost-competitive with current methods.

- To investigate opportunities for retro-fitting existing highway industry practice and devices with minimal-cost sensing and control, including man-in-loop control, in order to collect the information and project the decision-implementation required to apply factory-level and cell-level automated planning, process-management, and control technology in the highway environment.

- To identify opportunities for application or development of robotics technologies not currently employed in factory automation, where highway industry practices present unique new operations or processes that might be automated.

This set of objectives was intended to leverage existing expertise and knowledge accumulated in the factory automation experience of the last two decades, while avoiding the tendency to over-generalize and fail to recognize the unique challenges of the highway industry and its special problems. They were further interpreted within the context of FHWA's desire to identify both near-term and longer-term opportunities for impactful research, and to identify opportunities for stand-alone demonstration projects that could serve to catalyse interest of the highway industry and state and local governments in automation for highway programs.

Finally, it was intended that the study should become cognizant of, and build upon, the considerable body of work already done in this area, and the numerous contributions of other groups that have already studied various aspects of the issue.

4.1 Methods and Activites.

A study panel was assembled from NIST, academic, and industry resources. The makeup of the panel was chosen to reflect a broad-based expertise in various aspects of automation and robotics. Additionally, some members of the panel had relevant expertise in highway and general construction areas. One of the principal goals of the succeeding phases of the study was to educate the panel members as broadly as possible in the unique problems of the highway industry. Without such education it was assumed that the recommendations of the automation experts would likely be creative, but naive. Three major objectives of this education phase were 1) to gain familiarity with current technology, procedures, and practices used in highway construction, maintenance, and operations, 2) to understand the structure of the industry, its current practices and methods of doing business, and the regulatory climate in which it functions, and to try to understand barriers to adoption of automated methods, 3) to review the current state of the art with respect to applications of automation in this industry.

To address the first need, Dr. Woo of FHWA arranged three field trips for members of the panel. These took place in early 1993 and were hosted by the state DOTs of Texas, Georgia, and California. All three visits covered two days and included site-tours, meetings, and discussions. The sites visited illustrated a variety of construction activities, including surveying, several kinds of paving operations, bridge construction and decking, rebar laying, grading and filling, trenching and pipelaying, and materials handling. Maintenance operations included stripping and painting, re-paving, bridge-repair, pavement inspection, and traffic control. A half day was spent during the Los

Angeles visit touring the Los Angeles Traffic Control Center and discussing operations issues. Additionally, the panel members were able to view videotapes of other sites and operations provided by Dr. Tom West of CALTRANS.

The second need, an understanding of issues in the industry, emerges from the lessons of the last two decades in factory automation projects. The mistakes of the past reveal the ease with which the wrong targeting of problems can nullify the contribution of the most brilliant technical innovation. It is necessary to understand automatable processes in the context of the total chain of production in which they are imbedded, and to understand the economics of their contribution to that context. It is also frequently necessary to consider such non-technical barriers to adoption as labor displacement, human interfaces, regulatory and safety requirements, and environmental issues to evaluate the true potential, costs and contributions of potential automation projects.

Accordingly, to help the panel members understand these issues in the highway construction industry, a one-day workshop was held on November 4th, 1992, hosted jointly by NIST and FHWA, and attended by representatives of the highway construction industry including general contractors, major sub-contractors in important specialties, major equipment manufacturers and materials suppliers. Approximately seventy people were present. The meeting was arranged by the Robot Systems Division, and moderated by Dr. Richard Wright, Director of NIST's Building and Fire Research Laboratory. The meeting explored those issues which the industry saw as the principal problems driving their costs, deadlines, and quality control. In addition to the panel members, technical participants from FHWA and NIST, and outside technical experts attended the meeting as consultants. The panel members attempted to categorize and rank the issues raised, and to formulate them into guidance for interpreting the potential impact of the automation opportunities observed in the subsequent site visits.

A second meeting with contractors was arranged by the Texas DOT following the first site visit. At this meeting the panelists had the opportunity in a small-group format to ask specific questions about the operations they had seen and the potential contribution of automating them. They were able to hear the contractors' viewpoint on the business consequences and barriers to adoption of both specific proposals and general issues of automation. Many issues related to economic incentives and regulatory and labor concerns were discussed.

The third portion of the effort to understand the background of the problem, a review of the current state of the art, was first addressed by mounting a literature search and a technical workshop. Robotic Technology, Inc., conducted a search of trade association publications and journals, on-line databases, the Library of Congress, and university libraries. Several hundred directly-relevant and closely related items were identified which applied to FHWA concerns or closely-related topics. Items which related to research on technologies which could be applied to FHWA concerns, but which did not specifically allude to such applications were omitted, as this would potentially have included the entirety of the research literature in automation, machine vision, robotics, and similar fields.

As a check on the search strategy, a list of keywords was developed from the literature discovered, and a second contract was let to a search-specialist from the Institute for Scientific Information, who performed a three-day breadth-oriented search on the keywords from their database which covers most of the world's publications. This search returned 2500 items, of which most were false positives. No important or not marginally-relevant items were returned which were not in the original search. It was concluded that the initial search has found the majority of the relevant material. Copies of the search were made available to the panelists early in the study.

To further understand the current state of relevant technology, a second workshop was conducted in late April of 1993. This workshop focused on current research, and the attendees consisted primarily of academic and industrial scientists from the automation and civil engineering communities. The workshop was sponsored jointly with the National Science Foundation. The first day focused specifically on issues relating to highway construction maintenance and operations. The second and third days focused on technologies rather than applications, and covered the general area of robotics and automation applied to earthmoving, tunneling, site characterization, excavation, and materials handling. Many interesting papers were heard, and it was the consenus that most participants were substantially benefited from exposure to the current state of the art across a broad inter-disciplinary front. On the evening of the first day a discussion session was held at which the panel presented their preliminary proposals for highway automation projects to the participants for criticism and comment. A lively discussion ensued which resulted in several improvements to the proposed studies.

4.2 Proposals and Evaluation.

The ideas stimulated by these activities were summarized in a matrix of perceived opportunities for near-term to long-term efforts, categorized by area of highway concern and area of automation technology. Out of these general areas, perceived to have high potential payoff in terms of match between current or anticipated levels of automation technology and benefits to the highway industry, the panel selected a number of specific problems. These problems were selected to cover a representative range of time-scales and scope.

Individuals or small groups of the panelists then proposed research programs which in their opinion would address these issues. These pre-proposals focused on the nature of the research and the expected benefits to the highway industry. To evaluate the actual potential benefits of the proposed research programs and to attempt to assign an estimated dollar value to these benefits, the Civil Engineering Research Foundation (CERF) was given a contract to identify appropriate experts in the civil engineering community and assess their reactions to the proposals and to perform such other studies as necessary to draw conclusions on the expected benefits. CERF prepared questionnaires and descriptive mailings in consultation with NIST, evaluated responses, and held meetings with representative respondees for in-depth discussion of the issues. CERF performed an analysis of these results which was given as feedback to the panel of automation experts. Based on this feedback the panel made what revisions seemed appropriate to the proposals and prepared final forms of the proposals including estimates of time and cost for the proposed work.

At the same time, Robotic Technology, Inc., in consultation with CERF, developed an analysis of important factors for evaluation of true costs and benefits, which obviously may include many factors other than those ammenable to a strict accounting interpretation. The proposals, the CERF report, and the evaluation factors developed by Robotic Technology, Inc., together constitute a principal result of the study, which are presented in detail in the various appendices.

5 Results.

The principal results of the study, contained in several reports included as part of this document, were:

- A bibliography of the current relevant literature, including a brief review of some of the major projects covered in the literature.
- A general summary of the panel's impressions of the current state of the "fit" between automation and robotics technology and the needs and problems of the highway industry. The issues highlighted are summarized in the matrix of technological opportunities. Problems foreseen in adoption are also discussed.
- Several specific areas are further discussed in "white papers" which report more broadly on the relevance of these issues as a guide to further thinking in considering research needs. These represent topics which were found by the panel to be of broad importance across many issues of automation in the highway industry. Additionally, this section contains a report prepared by Robotic Technology Inc. surveying the state of Exoskeleton technology with respect to possible applications for highway construction and maintenance workers.
- The proposals for research programs in selected technologies, together with the CERF analysis of benefits and the study of evaluation criteria.
- A set of final proposals for particular research programs with specific deliverables and timescales.

SECTION: 4

SUMMARY OF RESULTS AND RECOMMENDATIONS

Summary of Results.

This section provides a guide to the various documents comprising the study, and a brief summary of their principal conclusions. Additionaly, in the first section, some global impressions which were obtained by members of the panel over the course of the study, and which are not directly contained in any one document are presented as a general guide and framework for interpretation of particular findings in other sections of the report.

1 General Findings.

The members of the study panel participated in a number of events focused on educating the panel with respect to current practice and state of the art in the highway industry, and with respect to the perceived needs and concerns of persons in all phases of that industry. These events included a workshop at which the panel members were able to interact with industry representatives, including contractors, materials suppliers, equipment manufacturers, and state DOT personnel. At the workshop, general sessions explored the reactions and concerns of the attendees to many issues in automation of their areas of expertise; smaller discussion groups provided brainstorming on particular topics. In three field trips, members of the panel visited highway worksites, and observed a variety of common activities in construction, maintenance, and operations first hand. On these field trips the panel members had the opportunity to speak with foremen, equipment operators, and other workers on the job. Additionaly, discussions were held with local contractors and with local state DOT engineers.

Out of these activities, the panel formed a number of impressions concerning issues and conditions in the highway industry with respect to automation. These impressions were influential in guiding the panel's technical proposals which are presented later in the report, but are not specifically contained in those proposals.

1.1 Barriers to Acceptance.

Self-evidently, the success of an automation revolution in the highway industry will depend on widespread adoption of new technology. A number of current conditions appear to act as barriers to acceptance of new technologies. In general, it is beyond the panelists' expertise to propose solutions to these problems, but it is worthwhile to point them out so that others may be motivated to address them.

- **Regulatory Climate:** The panel was repeatedly told of problems presented by conflict of proposed technologies with a variety of Federal, state, and local regulations. The industry is highly regulated, and in many cases the regulations have been written in a manner which implicitly assumes the current model of industry practice. Such regulations present a barrier to the introduction of new practices, methods, and technologies. Of particular concern are regulations which have been so-written as to actually incorporate references to specific, current technology in setting standards for acceptance, procedures for testing and inspection, or safety-related requirements.

- **Structure of the Industry:** The American highway industry is horizontally structured. Typically, contractors, sub-contractors, equipment manufacturers, and materials suppliers are all independent businesses. This contrasts with the situation in countries such as Japan, where a construction corporation is frequently a vertically-structured business that may develop and produce its own equipment. As a result, American equipment manufacturers are reluctant to spend development costs on new equipment which may present too high a risk for the small contractors who are their principal customer base. The American highway industry was characterized as an industry in which, "Everyone is trying hard to be second." The fragmented nature of the industry thus disinclines firms to adopt technology which has not already been proven to be profitable by someone else. This indicates a potential importance for demonstration projects as a means of speeding adoption of new technologies.

- **Contracting Practices:** In typical practice, a multitude of small independent contractors are involved in any large project. Often this includes not only firms speciallizing in different phases of project activities, but also firms of the same sort operating in different geographic areas, such as sections of right of way. This is not a great problem so long as overall project optimization is not attempted on short and intermediate time scales. However, one of the greatest benefits of automation in manufacturing has been just such 'real-time' optimization made possible by computerized measurement and control. Site-wide project integration, a major tool of automation for efficient operations, will be impeded by contracting practices which build islands of independent responsibility into project organization.

  Additionally the panel was frequently told that current contracting procedures, even where incentive clauses have been tried, often provide little incentive for the contractors to expend money to adopt new methods that provide such benefits as greater efficiency, reduced waste, reduced traffic disruption, improved quality, or even reduced time to completion. In particular, little incentive appears to exist for contractors to adopt methods that may reduce project life-cycle costs, as opposed to intial costs. In part these practices appear to arise from the lack of methods, until now, for giving contractors viable means to achieve these results.

The panel noted that many important tools and technologies for automation, particularly including automated methods for design, planning, measurement, and electronic information transfer are already commercially available to the highway industry, but are not widely adopted. While certain groups are making use of such methods, industry penetration appears to be much slower than is typical in the manufacturing sector. Factors such as those just mentioned, rather than any lack of applicability of atuomated methods to the industry, may explain this phenomenon.

1.2 Industry Needs.

The results of the industry workshop focused the panel members' attention on a number of perceived needs of the highway industry which were further amplified in the site-visits and other discussions. In general, these are not so much different in kind from concerns to which automation has been applied in other industries as different in emphasis and importance. This was a principal influence on the panelists' reccomendations from among the multitude of possible projects and technologies which could be considered. Some of the chief issues which were pointed out were:

- **Safety:** Highway construction, operations, and maintenance are inherently dangerous environments. Moreover, the unstructured nature of these environments compared to the typical factory environment makes control of dangerous conditions far more difficult. Aside from humanitarian concerns, injury represents a major economic issue in terms of lost productivity, health care costs, workers compensation, liability, litigation, and insurance. Automated methods for sensing and detecting danger, reacting to and controlling dangerous conditions, and removing humans from inherently dangerous situations are desired. This concern creates niche environments for fully-automated devices and teleoperated devices where they might not be otherwise justified on economic grounds of increased efficiency or quality.

- **Labor:** Labor costs were reported to be a more significant factor in the highway industry than in the manufacturing industries, perhaps in part due to the already-automated nature of most large manufacturing industries. At the same time, the typical jobs performed by human labor in highway tasks is far less structured than is the case in factory situations. As a result, it is not likely that current or foreseeable automation technolgy will be able to provide any wholesale reduction in the highway labor force through devices that directly replace humans. Rather, opportunities exist for increasing the efficiency of human labor through automated assistance. Possibilities range from automated planning for efficient use of workforce to teleoperated devices with partial automation of operator functions.

- **Equipment:** The industry is generally attuned to the value of improved equipment. However, a general consenus appeared to be that there is a great reluctance on the part of contractors or equipment rental firms to invest heavily in radical new technologies, and a disinclination to abondon existing heavy investments in current equipment. There are exceptions where a particular problem is seen as currently inadequately adressed by existing equipment, and these provide opportunities for the adoption of wholly new equipment technologies. However, in general, industry representatives expressed a desire for improved equipment technology in the form of add-ons or attachments which could be retro-fitted to existing equipment. This matches well with current automation technology, which can provide sensing, computor control, and enhanced operator interfaces that are easily retro-fitted to existing equipment at costs that are low in proportion to heavy equipment costs once development has been amortized.

- **Operational Efficiency:** This was seldom mentioned explicitly by the panel's industry contacts. However, it became the panel's consensus that a variety of specific issues repeatedly mentioned were facets of an overall need for enhanced efficiency of operations. Opportunities for automation technology addressing these needs include techniques of design for automation, automated planning and scheduling, dynamic as opposed to static optimization of operations, computerized site-integration, automated materials tracking, networked access to design and scheduling databases, and a variety of similar technologies long-used in other industries.

These and other less-frequently mentioned industry needs formed a background perception of the problems and opportunities facing automation of the highway industry as the panel considered possible specific problems and technologies in a search for recommended research and development programs.

2 Potential Automation Technologies for Research.

Working from the perspective developed in the workshops and site-visits, the panel discussed the spectrum of technologies which might be fruitfully applied to the highway industry, both today, and after various amounts of future research and development effort. The views and recommendations of the panel were compiled by Dr. Arthur Sanderson and summarized in two figures discussed here.

The matrix in Figure 1a presents in graphic form the intersection that the panel found between areas of potential application for robotics and automation in highway construction, maintenance, and operations on the one hand, and the state of current technology on the other. The potential areas for research are broken down in figure 1b into Near-Term, Medium-Term, and Long-Term opportunities. Near-Term implies that the basic technologies exist today, and that the effort required would be to integrate and apply these technologies to specific highway problems of interest to FHWA. Near-Term work is thought to be feasible in an 18-month time frame. Medium-Term work indicates that the panel believes that most technologies required for the application are available, but that some research is required for further technological development. This indicates that the general principles are thought to be understood and applicable to the task, but that some gaps in our understanding will have to be filled, and problems in application remain to be identified and solved. Experimentation will be required. Medium-Term work is estimated to require a time-frame up to three years. Long-Term work is that which the panel believes represents feasible targets for in-depth research studies aimed at discovering new and improved methods which will extend our technology in the directions required to apply it to the indicated problems. Time estimates for this sort of work must be open-ended, but the areas selected indicate those where the panel's professional opinion is that the research ought to be successful within five years.

TASKS/PROCESSES	SENSING & INSPECTION				LARGE-SCALE ROBOTICS				TELEOP AND HUMAN INTERFACE			INTEGRATION DESIGN, PLAN AND SCHEDULING			
	Vision	Misc. Sensory	Site Locating	Data Base	Earth Moving	Material Handling	Assmbly Paint	Driving/ Nav.	Lg.Scale Teleop	Manipul. Enhance	Inspec- tion	Design	Planning	Schedul- ing	Intelligent Control
Project Design				X								X	X	X	X
Planning and Scheduling				X								X	X	X	X
Site Layout			X	X								X	X	X	X
Grading	X	X	X	X	X			X	X						X
Paving	X	X	X	X	X			X	X						X
Trenching/Pipes	X	X		X	X	X			X	X		X	X	X	X
Retaining Walls				X		X			X			X			X
Concrete Construction				X		X			X			X			X
Rebar Assembly	X		X	X			X		X	X		X	X	X	X
Bridge Assembly	X		X	X			X		X	X		X	X	X	X
Site Materials Handling			X	X		X			X	X		X	X	X	X
Locating Utilities	X	X		X	X					X	X	X			X
Road Surface Inspection	X	X						X			X				X
Crack Sealing	X						X	X			X				X
Bridge Inspection	X	X	X	X					X	X	X		X		X
Road Striping	X	X	X				X	X			X	X			X
Paint Rem & Application	X	X	X	X			X		X	X	X	X			X

Figure 1a

Snow Plowing		X						X		X		X	X	X	X
Cutting Grass & Brush	X	X						X	X	X			X	X	X
Trash Collection	X					X				X		X	X	X	X
Traffic Cone - Place/Pick	X	X				X		X		X		X	X	X	X
Underwater Inspection	X	X		X						X	X	X	X	X	X
Underwater Construction	X	X	X	X	X	X	X		X	X		X	X	X	X
Tunneling		X	X	X	X	X			X	X		X	X	X	X
Safety/Security/Rescue	X	X	X					X	X	X		X	X		X

1. **SHORT TERM**

- Tying rebar -- especially on concrete beds.
- Weighing concrete to monitor flow during concrete paving.
- Improve pipe manipulation in trench -- reduce human hazard.
- Safety sensors around machines.
- Exploit current database standards.
- Add force feedback to machines.
- Expert systems for project costing.
- Automated planning and scheduling of rebar assembly operations.

2. **MEDIUM TERM**

- Site location system -- enhance human operator.
- Automated pipe laying and filling in trench.
- Real-time monitor of compaction -- soil and asphalt.
- Site layout and materials flow scheduling system.
- "Soft" links between machines for control and integration.
- Graphical display of project information system -- human interface and monitoring.
- Prototype project information system -- linked to design database.
- Road surface visual inspection.
- Apply design-for-assembly to rebar structures.
- Computer aids to traffic rerouting during job planning.
- Demonstration of two-machine cooperative manipulation.
- Tomographic inspection of bridge columns.
- Machines with exchangeable tools.
- Demonstration of concurrent engineering bridge designed for inspection and maintenance.
- Study of safety issues related to humans in the workspace of automated systems.

3. **LONG TERM**

- Automatically guided vehicles using site location system.
- Common database exchange format for site, materials, and operations.
- Real-time control of compaction.
- Integration of design database to planning and scheduling -- Project Information Systems.
- Multimachine coordination by networking and distributed control.
- Automated on-site assembly of rebar structures.
- Bridge inspection and repair.
- Life-cycle concurrent engineering for construction, maintenance, and repair of selected projects, e.g. bridges, trenches and piping.
- Design with improved, smart and environmentally sound, materials to enhance automation and maintenance.

Figure 1b

3 Literature Search.

In order to determine what efforts have already been made, or are under way, NIST contracted for a literature search which was completed early in the program and made available to the panel. The bibliography developed was updated throughout the course of the study. The bibliography, together with a discussion highlighting some significant representative published efforts is presented as a volume of this report.

In general, it was found that when the search excludes general research in automation technologies *per se*, such as "machine vision" or "artificial intelligence", and instead focusses on research and development aimed specifically at highway applications, the literature is surprisingly sparse. Even using a fairly broad definition of articles of interest, the literature appears to be comprised of several hundred published studies within the ten-year cutoff employed. This was confirmed with a broadly-defined computerized search of the entire technical literature base which yielded thousands of studies, only a few of which were both relevant and not contained in the initial directed search.

A second result is that a majority of the issues which the panel found likely candidates for research have been addressed in one form or another by others, not always with great success. On the one hand, it is encouraging that the panel's perception of significant intersections between technological possibilities and highway industry needs is confirmed in the perception of others. On the other hand, it is discouraging that these efforts have not had more impact than they have. Two conclusions which we draw from this are that careful consideration must be given to cost/benfits analysis of any proposed study, and that the effort cannot end with a successful research outcome. The sponsoring agency must follow through with an active program to inform and assist the highway industry in adopting the results of demonstrably sucessful and cost-effective programs.

4 Specific Opportunities.

Six specific proposals were put forward by the panel for evaluation of actual benefits. These problems have both long and short-term aspects, and in several cases the proposed work spans more than one time frame, with various benefits appearing at each stage. Some represent potential individual research programs, others represent possible large demonstration projects by consortia of investigators. They represent a selection, from the areas of study indicated in the matrix presented above, which the panel members felt were the most timely from the standpoint of a "quick hit" wherein the current state of the art in automation appears to mesh with significant issues in highway construction and maintenance. The proposals were presented and discussed at a special session of the technological workshop on automation for highway issues held by the panel in May of 1993, and revised on the basis of that discussion before presentation for cost/benefit analysis.

These proposals are summarized here, and their rational and anticipated benfits are inidcated. The volume of proposals presented to the Civil Engineering Research Foundation for analysis contains a more detailed discussion of each, prepared by various members of the panel.

4.1 Site Integration.

The primary objective of this work would be to very substantially reduce the construction time on highway projects, perhaps by as much as 50%, through the use of automation techniques now employed in manufacturing. Computerized design databases exist today which can be used as the basis of automated planning, scheduling and logistical control of materials and resources. Advanced control techniques can be used to dynamically reschedule the equipment on a site, as well as to coordinate the arrival of materials and relocation of men and equipment based on the current state of the site. In the short term, using design databases, survey databases, and on-site data entry, it is possible to do real-time global optimization of projects with man-in-the-loop interfaces, including equipment deployment and scheduling, and delivery of materials. Other advantages would include reduced materials waste and automated collection of data for as-built databases. The fundamental requirement is gathering and distributing information in a timely manner to optimize work for the entire site rather than just a small part of it.

Longer-term efforts could extend to semi-automated control of grading and materials-placement directly from plans and survey data through advanced operator interfaces, or to automated sensing and control of interactions between pieces of equipment, such as between trucks and concrete-spreaders/asphalt pavers, or between front-end loaders and bulldozers or graders.

4.2 Automated Bridge Decking.

The goal of this work would be to substantially reduce time and manpower required to deck or re-deck bridges, while improving quality and reducing the need for rework. The aim of this proposed national demonstration project would be to show that it is possible to incrementally add automated capabilities to today's technology in order to achieve this goal. Existing screeds used in bridge work already provide a basic, globally-referenced, physical platform. With this device as the common integrating target, researchers at many institutions could work towards implementing automated functions such as:

1. Subgrade inspection using photometric, range, and strain-gauge sensors.
2. Computer-aided design, organization, and tracking of rebar.
3. Laying down rebar, either individually or in sheets, including laying down the supports needed for the rebar.
4. Automated tying of rebar.
5. Monitoring concrete supply flow with respect to the subgrade profile and the design specification by use of optical, ranging, and strain-gauge sensors.

6. Inspection of the concrete slab immediately behind the screed to automatically correct pits or voids, and control overall deck profile to conform to specifications.

7. Other floating and tining operations automatically carried out and inspected.

4.3 Automated trenching and pipelaying.

This proposal would attempt to automate most phases of the trenching and pipelaying process through the use of sensors, automation controllers, and smart end-effectors for equipment. The advantages which would result from accomplishing these objectives include the automation of all in-trench operations to remove humans from trench which would greatly increase safety, and permit the cutting of minimum-width trenches to reduce time and decrease interference with adjoining structures, utilities, or landscape; the reduction of damage to buried utilities; increased efficiency of machines and operators; reduction of survey and site-layout time, and automatic creation of as-built databases for future utility maps. The proposed research would bring together in one specific application area many of the automation concepts from manufacturing which can be applied to construction work in the field. In addition, it proposes specific retro-fittable devices which can be used to increase the versatility of traditional equipment such as backhoe excavators. The inherent safety problems of trenching operations suggest this as a high-profile area for potential demonstrations of automated technology.

4.4 Bridge inspection and maintenance.

Develop improved alternatives to "Snoopers" for poistioning and manipuilating automated bridge inspection and maintenance operations. Elimination of workers from paint-stripping environments, and improved containment of lead-based paint and shot are examples of potential advantages of automation. In the short term, advanced control techniques can provide coordinated motion for devices adapted from existing machines. In the longer term, wholly-new forms of robotic devices could be designed for delivery of many inspection and maintenance services. Such machines would be programmed from databases describing each bridge. The bridge databases would be developed originally from "as-built" databases, which in turn would be developed during construction by noting deviations from "as-designed" databases generated during design. Each time a bridge is repaired or otherwise modified, an new "as-is" database would be generated. These "as-is" databases would constitute the input from planning and scheduling bridge repair, and for programming the robots to perform various functions such as inspection, paint stripping, and repainting.

Advanced robotic devices might be able to crawl along over and under bridges, automatically performing routine inspection, paint stripping, and repainting chores. Large bridges might have specially designed robots. Robots might be specially designed for classes of smaller bridges. Such robots might crawl along a bridge and its associated support structures and monitor a number of parameters that are a measure of the health of the bridge, such as macro-scale deformations, acoustic emissions, ultrasonic echo examination, paint condition, and chemical detection of corrosion.

4.5 Automated Pavement Inspection and Repair.

Currently human experts are required to visually inspect road surfaces. Many attempts have been made to apply machine vision to this process due to the very large amount of inspection that must be performed, but none has yet been sufficiently successful. The objective of this proposal is to develop an inspection system for roadway defects such as cracks with performance better than that of human inspectors. The minimum detectable crack size would be less, so that preventive maintenance could be carried out earlier, leading to increased savings in repairs. Quantitative measures of performance,detection rate, and false-alarm rate, could be accurately characterized. The goal would be to carry out the inspection (and, for defects of limited severity, the repair) at highway speeds. Much more roadway than the currently limited sample could be inspected, and, if repair could be carried out simultaneously, inspection and repair would become a one-pass operation with no need for road closing.

4.6 Temporary bridging.

Deployment of modular temporary bridging systems by automated means could provide several classes of benefits associated with different time-frames of technological development.

NEAR TERM - Temporary bridging for traffic diversion around bridge repairs can be placed with increased speed and efficiency by integrating existing new technologies for modular bridging with recently-developed robot crane technology which provides stable control of heavy lifting in six degrees of freedom.

MID TERM - Rapid and ecologically non-invasive bridging of wetlands during construction of new bridging could be accomplished with further extension of these technologies. The suspended Stewart platform crane technology can emplace lightweight modular bridging over ecologically-sensitive sites with little or no footprint. The net benefit would include elimination of costly reconstruction of damaged habitats, as well as minimal ecological intrusion.

LONG TERM - Relocateable temporary bridging to carry traffic over highway repair sites is an idea with a long history. Until recently the technology to make such proposals realistic has not existed. It now appears that combinations of recent developments in deployable bridging structures and robotic lifting and positioning technology make it reasonable to attack this problem in a serious manner. If this can be achieved, very substantial benefits to the economy would result from minimizing lost commuter time and delay of goods and services due to traffic congestion at repair sites.

5 Cost/Benefit Analysis.

A booklet containing the above overviews of the proposed projects, and their complete texts, together with a brief review of the mission of the study program was presented to the Civil Engineering Research Foundation (CERF) for analysis. This booklet is included as a volume of this report.

The CERF findings, also included as a volume of this report, presents in detail the methods employed and the results obtained. The methods inlcuded questionairres and surveys of knowledgeable experts, followed by an in-depth analysis of a specific 'real-life' scenario for each proposed program's results under the assumption that the research could be brought to a successful conclusion. In addition, CERF obtained more qualitative information concerning perceptions of relevant professionals with regard to the need and desireability of the proposed results.

The experts participating in the CERF study included industry professional engineers, engineering faculty of academic departments, and state DOT engineers. They attempted in each case to arrive at estimates of the cost of adoption of the proposed technologies, and to place an estimated value on the expected benefits. Great difficulty attends any such estimates when it is attempted to address aspects beyond simple initial cost. The greatest dollar value to the economy of proposed new technologies may reside in such things as increased life span due to more uniform construction quality, or hours saved in movement of goods or workers due to decreased traffic disruption. The estimates must then be treated with caution, but represent the experianced professional judgement of knowledgeable professional engineers.

5.1 Savings relative to current practice:

In summary, the CERF analysis found four of the studies to have significant potential benefits based on the scenarios investigated. These were, in order of potential savings over current practice:

1. Automated pavement inspection and crack-sealing.
2. Automated bridge inspection and maintenance.
3. Automated bridge deck construction.
4. Site Integration.

This rank-ordering could be significantly affected by the asumptions and scenarios used:

The pavement inspection and sealing proposal depends heavily on the ability to successfuly seal transverse cracks at speeds of several miles per hour. The CERF experts accepted this assumption, but recommend that this technology be demonstrated before other aspects of the proposal are pursued.

The bridge deck construction proposal was evaluated based on a relatively small bridge. It is probable that it would show greater potential savings over current practice on larger bridges.

The site-integration proposal showed 20% savings over current practice. However the scenario evaluated, an asphalt resurfacing project, involves relatively repetitive, sterotyped procedures progressing serially along a stretch of road. This is arguably a worst-case scenario for demonstrating potential savings from this approach. More complex and heterogenous projects might show significantly higher savings.

5.2 Overall benefits to the industry and the economy.

The evaluation based on savings over current practice must be weighted by the percentage of highway industry effort subject to improvement. When the results are adjusted on this basis, the relative ordering of the proposals by benefit changes. Bridge construction and inspection, while important problems, represent a relatively small proportion of total expenditures for highway construction maintenance, and operations. Inspection and sealing of highways on the other hand must be continuously carried out on essentially the entire national highway system, and involves significant costs to the economy through delay of traffic. Site integration, which offers a smaller per-project percentage savings, is nonetheless a technology applicable to virtually all highway industry activities so that the total potential savings become enormous.

Taking these factors into account, the CERF study estimates that the total benefit of site-integration technology for highway construction and maintenance is in the range of 8*billionto*16 billion per year for the United States. Automated highway inspection and crack-sealing, in addition to direct cost savings, has potentially high returns in reduction of indirect costs by proper maintenance of the nation's highway system. Among these are reduced fuel consumption, reduced transportation costs, reduced vehicle repair, and increased safety. While it is almost impossible to attach a reliable dollar estimate to these benefits, it is clear that they represent potentially enormous benefits to the economy through the sheer numbers of vehicles and persons affected.

After weighting the potential contributions in this fashion, the CERF study highly recommended two proposals for further development:

1. Site-Integration.
2. Automated Pavement Inspection and Crack-Sealing.

Automated bridge inspection and maintenace, and automated bridge deck construction were considered potentially beneficial, although of lesser overall economic impact.

Atuomated Trenching and Pipelaying, and Rapid Temporary Bridging were not considered by the CERF respondents to provide substantial benefits. (However, the analysis of the pipelaying was based on the conclusion that it could not fully eliminate the need to have men in the trench, a point which the author of the proposal has addressed in the revised final proposal, and which should be taken into further consideration.)

6 Final Proposals.

Following the CERF analysis, the authors of the technology proposals prepared specific research and devlopment proposals with detailed budgets and deliverables for consideration by FHWA. In the case of some this is essentially the addition of a level of time and effort statement and a proposed budget for the technological development contained in the proposal presented to CERF. In the case of others, a more specific near-term scenario was developed for evaluating and demonstrating a particular application of the technology; for example, a bridge-construction project was proposed as a means of evaluating the the Site-Integration concept.

The final proposed projects present a spectrum of opportunities from relatively small to quite large efforts, and from relatively risky research to integration of existing technologies. In general, the funds requested for research are insignificant by comparison with either the adoption costs of the technologies by industry, or with the potential benefits of a successful adoption. However, they may still be relatively large with respect to available research funds. In this regard, they offer a range of opportunities for funding, and many offer flexible options for staged funding of phases of a project over time.

7 Other Items Included.

It should be recognized that the final proposals presented here each represent only one idea concerning possible approaches to one of the intersections between needs and technology identified by the study panel. It is hoped that the study in its entirety will serve to identify many potentially fruitful areas for research funding, and help to stimulate many others to advance proposals for other approaches and other fruitful areas of research. To this end, several other documents generated in the course of the study are included as general results even though not bearing directly on the proposed studies.

1. **White Papers:** Several panel members prepared "white papers" addressing issues in automation with potential relevance to highway issues

from a more general perspective, including such topics as Design for Automation, Automated Planning and Scheduling, and Robotics and Teleoperation. A contracted review of the current status and potential applications of powered human exoskelatons is also contained in this section.

2. **Technology Workshop:** FHWA, NIST, and the National Science Foundation jointly sponsored a three-day invitiational workshop to review current progress in technology for automation of construction and site preparation. The first day of this conference was devoted to technology for highway construction, maintenance, and operations. A summary of the proceedings of this day, and abstracts and viewgraphs of the presentations is included in this report. The proceedings of the entire three-day workshop will be published at a later date by the National Science Foundation.

3. **Evaluation Criteria:** The CERF report focused, by design, on evaluation by attempts assign dollar values to costs and benefits. However, CERF attempted to identify other issues in industry perception of the proposed study, and in general it is recognized that assessing the real social and economic costs and benefits of such projects is difficult at best, and frequently dolar value may be a poor measure. An independent effort was comissioned by FHW to devise a procedure for identifying evaluation criteria. The results of this effort were not ready in time to apply them to the proposals contained in this report, but may be useful in evaluating future proposals. This study is included as an auxilliary document of relevance to the study.

4. **Videotapes:** Several videotapes were generated during the study, and are included as part of the report. These include the full proceedings of both workshops, and a set of tapes of typical highway operations contributed by Thomas West of CALTRANS.

SECTION: 5

WHITE PAPERS ON SELECTED TOPICS

Robotic and Telerobotic Technology

A principal goal of the study was to assess the applicability of current robotics technology *per se* to the domain of highway-related activities. By this we mean autonomous or teleoperated mechanisms as opposed to automation technology in the more general sense.

True robots are mechanical devices whose actions may be programmed. Frequently they incorporate sensing to obtain information about their environment, which is then used by the program in determining the actions. This type of robot is most often found today in factory environments performing tasks such as welding. Robot vehicles are also in current use to deliver parts and materials. Telerobotic devices are similar to true robots mechanically, but the interpretation of information from the sensors, and the decision-making necessary to controlling their actions is performed by human operators. Such devices are frequently used for exploration or manipulation in hazardous environments. A continuum between telerobots and true robots can exist when substantial automated interpretation of sensory data is performed before presentation to the operator, and substantial programmed elaboration of general commands by the operator is done under program control.

With today's technology, true robots are limited to very highly structured environments for practical applications. Environments such as assembly lines are needed to provide sufficient control over positioning of parts, timing, illumination, and other variables to enable robots of cost-effective simplicity to be employed. To the degree that such variables are uncontrolled, a robot must have more intelligence, more flexibility of behavior, and more elaborate sensing in order to adapt its behavior to more variable conditions. In particular it must have a robust set of responses to all possible conditions that may arise in its environment. A great deal of current research is focused on extending robot capabilities to less constrained environments. Experimental devices exist which are substantially more capable than typical commercial robots in all of these respects. These devices, however, are far more expensive than robots employed in industry; they are not very robust or reliable in their behavior, and few if any have tried to combine advanced capabilities in more than one area of the technology.

Telerobotic technology on the other hand has made rapid strides in the ability to function effectively in unconstrained environments. Because the most difficult aspects are handled by the human operator, the performance is typically robust. Because adequate effectors and sensors need not add greatly to the cost, and heavy, high-speed computing requirements are avoided, these devices can be quite cost-effective. Recent advances in virtual reality technology promise to enhance the effective use of telerobotic devices by increasing the operator's sense of presence and enhancing his ability to control the device. While telerobotic devices are invaluable for hazardous or unreachable environments, and overcome the true robot's limited judgement and versatility, they cannot provide some of the benefits that have made true robots desirable in industry. These include suitability for tedious, repetitive work without loss of attention, and consistent reliable quality. Because a telerobotic device does not typically make an operator more efficiant, no gain in productivity is usually obtained.

Potential highway applications

The environment, cost structure, type, distribution, and automatability of tasks are quite different in the highway industry than in typical factory automation applications. Whereas the labor-intensive jobs in factories tend to be repetitive assembly line types of work, the labor-intensive jobs in highway applications tend to be unstructured tasks performed by men with rakes or shovels responding to needs that they see, or to directions from a foreman phrased in very general terms (exceptions such as rebar-tying of course exist.) It is not reasonable to consider robotic equivalents of these typical highway workers, even in the fairly long term. The foreseeable extensions of today's technology will not support this degree of autonomy in anything approaching a reliable and cost-effective form without new breakthroughs in fundamental science.

It is however reasonable to consider reducing the number of tasks requiring such unstructured hand labor through the use of robotics technology. One way in which this can be accomplished, as discussed in other parts of this report, is by overall automation of the construction process through site-integration and automated planning, which would provide more efficient use of equipment, materials, and labor, and enhance worker productivity. It can also be accomplished in part by robotics technology applied to improve consistency and repeatability of devices such as excavators, paving trains, screeds, and similar machinery, the current operation of which frequently requires a great deal of hand work to correct minor deviations.

This might best be approached by semi-autonomous telerobotic strategies, in which machinery controlled by human operators would employ a suite of sensors and controls to keep the fine-grained behavior of the device within specified limits. For example, while the operator might control the general forward motion and operations of a slip-form paver, low-level robotic systems could sense deviations from straight progress, variations in material flow, or irregularities in application as they developed, and take corrective actions to adjust them. Simple variations on this theme are already employed via electrical and mechanical means on asphalt pavers. More ambitiously, such low-level robotic control could be employed to coordinate activities among interacting machines such as concrete spreaders and slip-form pavers, or asphalt trucks and asphalt pavers, to ensure uniform and consistent application. Simple semi-autonomous systems of this sort might improve quality and efficiency of the machinery itself and at the same time reduce the need to keep crews standing around prepared to step in with hand labor when needed.

Possibly the one area where full-robotic systems might conceivably be employed in highway construction is materials movement. Automated delivery vehicles are frequently used in factory situations, and robot vehicles capable of negotiating unstructured terrain with fair speed and reliability have been demonstarted in research settings. A variety of military missions for such vehicles has been investigated. Very significant advances would be required to bring this technology to a level of reliability and cost effectiveness at which it would be competitive with human-operated trucks. This is particularly true given that overall job-site control, as detailed in other places in the present study, can already achieve most of the objectives of such robotization, including control of dispatching, routing, timing, and tracking of materials simply through interfaces to a human operator in a standard vehicle. Given this, the savings represented by eliminating the human driver are unlikely to cover the cost of fully-robotic vehicles for field conditions in the foreseeable future.

One of the principal demands that automation technology can address is safety. Whether for economic or humanitarian reasons, this is seen as a major area of demand by the user community. There is thus a demand to remove the workers from the immediate area of hazardous operations, even if it is not possible or practical to replace them with fully-automated equipment. This suggests that teleoperated devices, and the associated research issues of human interfaces and control for such devices, may be a major research opportunity. Possibilities include teleoperation to remove workers from trenches, and to remove workers from areas under suspended loads. Typically, in trenching, expensive forms are required if men are to operate in the trench. While automated positioning equipment and self-locking pipe joining systems could be readily provided, it is inevitable that something will occasionaly jam or otherwise require human intervention in the typical field environment. Unless this can be eliminated, forms would still need to be placed so that workers could be allowed into the trench. A possible solution is the development of general-purpose field telerobotic manipulators with senory feedback that could be quickly postioned and provide a remote "hands on" capability for general-purpose human intervention in any sort of hazardous construction situation.

It was also frequently observed that it would be beneficial from the standpoint of the contractor's initial cost if automation could increase the efficiency of human operators and/or decrease the manual skills required of them. This suggests that teleoperated devices could be made even more attractive if they were provided with some semi-autonomous functionality which could amplify the speed and accuracy of a human user. Taken together, these two issues suggest that semi-autonomous, teleoperated devices, with advanced human interfaces, represent a research thrust which would meet perceived needs and would be readily accepted by the user community. At the same time, they represent an area in which existing technology can be exploited for near-term results.

A closely-related research area is human-assist devices intended to enhance the strength and structural capacity of human workers. At one end of this spectrum are simple devices, already in use in some European construction programs, which provide an individual worker with enhanced lifting capabaility, such as for moving brick or similar loads. Such devices not only increase worker productivity, but reduce the incidence of back injuries. At a more advanced level, "exoskeletons" may be considered. These are essentially powered suits worn by a human to increase strength and in some envisioned cases speed of movement and/or sensory capabilities as well. These devices are technically different than telerobotic devices in that they do not remove the user from the point of operation, but much of the same technology is involved. Such devices have a long research history for military and industrial use, but this apparently simple concept has met with formidable difficulties. Recent advances in materials and controls suggest that further research may overcome some of the difficulties. The current state of exoskeleton research is treated in a companion paper in this study.

One of the principal reasons for the difficulty of exoskeleton development lies in the fact that we cannot achieve the strength to weight ratio of biological systems with mechanical systems providing useful power enhancement. This means that from the standpoint of the human operator, even with appropriate force-feedback and other refinements, the result of attempting to make a movement is at odds with the result expected by the reflexes of the human nervous system, presenting an enormous problem of human interfacing. This appears to be less serious for humans operating a teleoperated grasping arm, for example, than for a human attempting to walk, stoop, and carry in a natural manner inside of a powered exoskeleton. Thus, while this is an interesting and potentially profitable research area, it is one in which the simple extension and integration of available technologies is unlikely to provide an adequate solution.

Most equipment manufacturers currently appear uninterested, without economic incentives, in rushing to produce automated equipment, although most have some research in the area. The end-users similarly indicate reluctance to invest in new types of equipment. The remarks from the equipment manufacturers were that we should seek to provide automation and enhanced functionality through add-ons and attachments to existing products. This would be acceptable to the equipment purchaser as well, since the basic investment would be in standard equipment with the add-ons available where they were perceived to add value. In the long run, FHWA may want to provide incentives which will change these attitudes. For the near term, however, they suggest robotic technologies to be explored which would provide real benefits while addressing these current concerns, and thus facilitate adoption.

Technology which could be easily fitted to existing equipment in this manner at comparatively small expense includes sensors and electronics for command and control of equipment and for reporting of position and activity. This would have high leverage in the sense that it is a technology which would be applicable to most existing devices, and it is mostly available today. It is unlikely that anyone will soon completely remove operators from heavy equipment simply for safety reasons alone. However, enhanced efficiency and repeatability could be obtained by bypassing the operator in normal operation, and allowing remote sensing, planning and control systems to control movement in operations such as grading, spreading, dumping, trenching, compacting, and the like. It is probably of little value applied to a single machine in isolation, but as the equipment-level extension of a more global thrust in the site-integration technology described in other portions of this report, it can nonetheless play an important role.

Another reasonable candidate for retro-fitting existing equipment with new technology would be provision of the low-level semi-autonomous controls for enhancing precision and speed of operation discussed earlier. A simple current example is laser-controlled blade-height adjustment of graders in levelling. Much more ambitious operator-assist functionality is a near-term possibility with relatively simple sensing and control retrofits plus the addition of modest computing power. Because a human operator would be present, most of the difficult problems of full automation are avoided, as these typically arise in non-routine situations. In addition to improved speed, consistency, and accuracy of operation, such developments could be expected to allow the operation of such equipment with less-skilled personnel than is currently required.

WHITE PAPER

"Design Issues in Automation for Road Construction, Maintenance, and Operations"

Prof. Arthur C. Sanderson
Electrical, Computer, and Systems Engineering Department
Rensselaer Polytechnic Institute
Troy, NY 12180

Submitted to:
Robot Systems Division, NIST, in conjunction with the first Workshop on Automation for Road Construction, Maintenance, and Operations, sponsored by the Office of Advanced Research of the Federal Highway Administration (FHWA).
November 18, 1992

SUMMARY:

Key opportunities for technical innovation in automation for road construction, maintenance, and operations lie in the process and integration of design. *Design for automation* may result in reduced cost, more efficient maintenance and operation, improved quality, and safety benefits. Examples include "self-maintaining" roads and bridges, deployable robotic structures, and cooperative robots. *Design integration* is vital to successful automation and incorporates design information with construction and maintenance operations. Examples include site positioning and terrain mapping, human interface and user operation of automation, and distributed architectures for robotic systems. *Design and project management* brings design information and processes into the level of project organization. Automated sequence and process planning, advanced database systems, and materials handling and tracking systems are important examples of technical tools which impact elements of project management.

1. INTRODUCTION

Road construction and maintenance projects heavily rely on technologies for materials, processes, and equipment. As generally publicly funded projects, these activities are closely tied to regulations and specifications which govern the procedures and set the standards for final performance. The constraints of the contracting and evaluation process sharply defines the way in which technological innovation occurs in the road construction industry and shapes the types of innovation which take place. Within this domain, the major motivations for new technologies include reduced costs, improved quality and functionality, and improved safety for workers and the public.

In many areas of application where automation has been successfully applied, better understanding of the design process itself has been a key to that success. In manufacturing, for example, it was found that up to 80% of final costs were determined at the time of product design. The choices made in the product design constrained many of the subsequent decisions in manufacturing, including manufacturing processes and equipment. Once the design is "handed off" to the manufacturing organization, the options are limited. In road construction, a similar relationship holds, except that the impact of design decisions carries even more strongly into the long-term areas of service and maintenance of roads and structures. Thus, design of roads and structures, as well as the design of equipment and procedures, and their relation to regulations and specifications, dictates costs and technologies. Improving the effective utilization of new technologies in road construction and maintenance will require careful review of the design process.

In many manufacturing industries, the recognition of the importance of the early design decisions, and the liabilities associated with decoupling design from manufacturing, have lead to extensive efforts toward a methodology of "concurrent engineering". Concurrent engineering has emerged as a methodology which incorporates both organizational and technical tools to foster closer cooperation between design, manufacturing, and marketing groups within a company. Such approaches as "tiger teams", small interdisciplinary focused teams for new product development, enhanced databases and computer-aided engineering (CAE) tools, and automated process planning methods are being developed and used experimentally to improve productivity and enhance the ability of companies to respond to rapidly changing production demands.

A similar need exists in the road construction industry to merge more closely the design, equipment selection, and process planning phases of projects. Some of these concepts are embodied in efforts toward "life cycle value engineering" which try to systematically address priorities throughout the design, construction, and service phases of a project. As in manufacturing, these changes will be accompanied by both organizational and technological changes in order to effectively impact the activities. In the following sections, this white paper outlines some important issues which affect the technical methodologies which bear on these problems, and tries to suggest some specific topics for short and long-term investigation which could facilitate the impact of automation and robotics on road construction, maintenance, and operation.

2. DESIGN FOR AUTOMATION

The effective use of automation and robotics often requires that processes and products be redesigned to better adapt to these technologies. Processes and tools which have been designed primarily for human use are often not directly accessible to automated methods, and attempts to directly substitute a robot for a human worker have often been unsuccessful and unproductive. Designing a robot which could pick up a hammer and a nail and drive the nail is an extraordinarily difficult technical task; however, designing a machine which could align a power nailer with studs on a flat wall is quite feasible. Redesigning the wall and the building for modular factory production with automation, and modular assembly on site may offer still further gains in productivity. There are many such examples of innovations in products and equipment which facilitate more efficient production and lead to gains in quality, safety, and productivity.

A research or development program in automation and robotics should systematically examine opportunities for redesign for automation of both construction and maintenance. The program might focus on several areas of opportunity for improvements:

1. Reduced cost through more efficient methods, increasing the productivity of human operators and reducing waste.
2. Improved quality through more consistent operations, improved execution in hazardous or difficult tasks.
3. Improved safety by changing the process or keeping the human out of dangerous situations.

Some examples of design innovations which could be investigated in this area would include:

- 'Self-maintaining' roads and bridges:

New materials and *sensors* will make it feasible to design structures which have built-in sensors and monitoring devices to report deterioration in integrity. Internal adjustments of structural loads or reduction in some modes of vibration will reduce the rate of deterioration of such structures.

Integrated maintenance systems would have built in mechanisms to facilitate periodic service of the system. For example, a bridge might be designed so that a climbing robot can easily scale the structure, providing inspection and repair as needed, without subjecting the human to difficult and dangerous situations.

- Deployable temporary structures:

Many types of construction require temporary structures for scaffolding or shoring. These structures are assembled and later disassembled. The characteristics of these structures are often critically important to safety, but since they are not permanent, are not often designed or constructed with the greatest care. Deployable robotic structures provide a new approach to these problems, offering active mechanisms in a modular form which can be predesigned and adaptive to specific situations. A specific example would be the use of deployable robotics for shoring of trenches. By actively adapting to the spacing and shape of the trench walls, the systems can be lowered into the trench and automatically 'fit' to the shoring requirements without extensive assembly and without humans working in the trenches during the construction phase. While eventually, trench work for piping and other utilities may be entirely automated, use of deployable trench shoring would be a practical and feasible step. Deployable robotic structures are a new area of robotics research and development, and have important practical uses for both local and remote deployment. Development of prototypes of deployable robotic systems is currently underway in our laboratory.

- Cooperative robots for heavy lifting:

Many construction and maintenance tasks require lifting and manipulation of large and heavy objects. While such motions are often assisted by cranes and other mechanical devices, the local positioning is often done by humans. These manipulation tasks are difficult and dangerous. The design of better cooperative interaction among devices including cranes and robot arms, would enable more precise manipulation without direct human intervention in the hazardous area. Dual robot arm capability under autonomous and teleoperated control is a technology which is just beginning to have practical application. In our laboratory at Rensselaer, we have demonstrated the use of dual arm robotic systems for space truss construction tasks.

3. DESIGN INTEGRATION

Improvements in the design process and more effective utilization of design information require better integration of the process among the design information, the human operators, and the process equipment. This type of design *integration* is vital to successful automation. Several aspects of this integration problem are characteristic of the construction environment, and distinct from other applications such as manufacturing:

- Uncertainty in the unstructured environment of a construction site leads to the need for **automated site positioning** and **terrain mapping** systems. These systems would provide on-site verification of relative and absolute positions of objects and equipment. Much of the problem of accurate construction is concerned with creating a precise structure in an environment of imprecise landmarks and imprecise materials. Automated techniques can greatly improve the precision of this process and, at the same, time provide an environment where it is easier to design and integrate automated machines and procedures. In our work at Rensselaer, we have developed computer-based pose estimation systems which utilize special markings on objects for registration of position and orientation in a complex work environment.

- The human is active in the workspace with automated equipment as supervisor, teleoperator, or co-worker. The modes of this interaction have not been adequately explored and understood, and a significant effort should be placed in the design of techniques which address the user-robot interaction in a broad sense. The **"user-in-the-workspace"** scenario is an attractive working paradigm, but also offers significant new safety issues which must be addressed.

- The construction environment is **distributed** in nature, having multiple machines and activities going on at the same time. It will be important to develop an approach to the design of **distributed architectures** for such an environment, which provide coordination among different activities and support task sequencing which will correctly accomplish the task. In our laboratory, we have developed tools for coordination of discrete task events as part of a distributed architecture for coordination of multiple robots in complex tasks.

4. DESIGN AND PROJECT MANAGEMENT

As described previously, many of the improvements in design-manufacturing integration have occurred through improved management and organization techniques. These techniques, along with technical innovation, have enabled the more efficient flow of information among designers, manufacturers, and marketers. Through these methods, critical decisions are made with a broader perspective of the impact of those decisions on the later steps in the process. In this section, we emphasize some of the technical innovations which could facilitate this improved transfer of information in the road construction and maintenance industry. Many other issues in organization and management are key components of the automation process, including education and training, interactions among industry, labor, and regulators, mechanisms for partnering in technology development, and provisions for transfer and exchange of current information and experience, both internal to U.S. programs, and cooperatively with other countries.

- Automated Task Sequencing and Process Planning:

A project is executed as a sequence of procurement and construction tasks. The organization of these tasks often defines the productivity achievable on the project. New methodologies are emerging which facilitate the efficient generation of process plans from design specifications, and the generation of evaluation criteria which encourage the iterative revision of process plans for improved efficiency of the project. One example of this type of planning is based on work which we have done with NASA for the generation of process plans for the building of space truss structures. Based on the design of the truss itself, we were able to utilize the product design constraints to produce feasible sequences of assembly for the truss. Evaluation of the alternative process sequences encourages iterative changes to improve the process choice before the design is finalized.

- Database systems:

Process planning and effective management of large projects requires the evolution of large and comprehensive database systems which can track and access information as needed. These systems are increasingly available commercially and provide fundamental tools for improved project management. In construction or manufacturing, the problem is often that there is a diversity of types of information, for example, costs, materials, structural details, and labor requirements. Merging of these types of information and efficiently accessing information as needed are difficult tasks to achieve. Recent innovations in so-called **meta-database** systems helps to organize these factors. Creation of the database system and strategy for management of information at the time of the design is important to effective project management.

- Materials Handling and Tracking:

Procurement, delivery, and manipulation of materials is a major part of the construction process. Maintaining accurate and up-to-date information is a key factor in a successful project. The key problem is the up-dating of information based on site conditions and actual operations. This automated tracking requires sensor-based feedback at the project site of the location and disposition of all materials delivered to the site. This tracking system may be an extension of the project database and project planner, but requires physical linking into the materials on the site. Mechanisms for doing this have been described and proposed, and would be an important topic of development for automation and improvement of construction operations.

SECTION: 6

BIBLIOGRAPHIC STUDY

AUTOMATION/ROBOTICS FOR ROAD CONSTRUCTION, MAINTENANCE AND OPERATIONS: LITERATURE SEARCH FOR THE STATE-OF-THE-ART

Prepared By:

Robert Finkelstein

Robotic Technology Inc.

10001 Crestleigh Lane

Potomac, Maryland 20854

December 1992

CONTENTS

PURPOSE

The purpose of this report is to document, using sample extracts from a survey of the literature, the state-of-the-art of automation/robotic technology for road construction, maintenance, and operations. The relevant literature was assembled and delivered to the Robot Systems Division of the National Institute of Standards and Technology (NIST).

BACKGROUND

Automation technology promises to increase safety and productivity while reducing costs and the adverse impact of work sites on traffic. The new FHWA automation/robotics program emphasizes finding near-term solutions to pressing problems and fielding useful equipment.

In recent years there has been significant progress in the development of Government and commercial software and hardware systems for various automation applications. Advanced sensor systems for inspection, automated databases and program management software, and robotic vehicles are some of the new automation technology which promises to benefit road construction, maintenance, and repair.

For example, robotics for military applications, including the development robotic excavators, dozers, and inspection vehicles with various kinds of sensors, can be modified for road construction applications. Robotic systems have also been developed for coal mining, hazardous waste cleanup, and building construction. In 1990, the California Department of Transportation (CALTRANS) initiated the Automated Highway Maintenance and Construction Technology Program; the Japanese have had active programs for nearly ten years.
Automation of road construction, maintenance, and operations can increase safety (highway workers suffer more than 5,000 injuries and nearly 800 deaths per year), productivity, and quality, while reducing costs and the adverse impact of work sites on traffic.

Potential functions include:

Construction:

* Clearing/sediment control
* Earthwork
* Shoring
* Paving
* Marine
* Bridges
* Utilities

* Signing
* Rehabilitation

Maintenance:

* Concrete patching
* Repaving
* Resigning
* Bridge/tunnel repair
* Plowing/sweeping
* Painting/striping
* Mowing
* Inspection of roads and bridges

Operations:

* Special traffic control for construction
* Highway system management
* Safety management
* Incident management

CALTRANS, for example, has been developing automation systems for road maintenance, including: automated pavement marking, automated paint striping, automated litter collection, and automated crack sealing.

Other near-term robotics projects under discussion include: a flag robot for temporary traffic control; a robot for painting road letters; a robot for placing and removing traffic cones; a robot for constructing sound isolation walls; a robot for clearing hazardous material after accidents.

Automation could connect sensors and equipment on a job site with project databases and management software. For example, as an automated excavator performs its job, it could report its movements and accomplishments to a database which, in turn, automatically updates project progress records and revises, if necessary, the work plan. Inspection of road surfaces and bridges could be accomplished automatically with, video and other sensors, using automated sensor processing techniques. The results of the inspection would be organized and entered into a database automatically as the inspection took place. The inspection itself could be accomplished using a robotic vehicle.

There has been research and development in applications areas relevant to road construction, maintenance and operations, but much of the work focuses on building construction, or military applications, or coal mining (the pertinent literature, delivered by Robotic Technology Inc. to NIST, is listed in **Appendix A**). A more focused effort on highway applications is needed, so the Transportation Research Board is offering their first sessions dedicated to road construction robotics and automation in their 72nd annual meeting (January 1993). Examples of previous work on automation/robotics for road and bridge construction, maintenance, and operations include:

* Expert System for Management of Low Volume Flexible Pavements
* Artificial Intelligence To Locate And Repair Potholes
* Automated Surveying
* Automated Position And Control Systems Using Lasers And Electromagnetic Signals
* Bar Code Applications in Construction
* Robotic Excavation
* Artificial Intelligence And Computer Simulation To Plan And Control Earthmoving Operations
* Computer Aided Rigging Design System
* Object-Oriented Programming In Robotics Research For Excavation
* Pavement Distress Video Imager To Quantify Pavement Cracking From Video Images
* An Expert System For Optimal Tower Crane Selection And Placement
* A Knowledge-Based Approach To Construction Coordination
* An Object-Oriented Simulation System for Construction Process Planning
* Intelligent Database Applications On Signal Maintenance Activities
* Knowledge Representation for Fatigue Evaluation
* A Computer Assisted System For Construction Robot Implementation Logistics
* Knowledge Elicitation Techniques For Construction Scheduling
* Expert Systems for Bridge Monitoring
* Adaptive Control for Robotic Rebar Bending
* Construction Schedule Generation Using AI Tools
* Automated Pavement Surface Distress Evaluation
* Computer Analysis of Segmentally Erected Prestressed Concrete Bridges
* An Expert System For Design And Analysis Of Highway Bridges
* Investigation Of The Bridge Vehicle/Superstructure Interaction Problem Via Computer-Based Methodology
* Database Design For Seismic Evaluation Of The San Francisco Bay Bridge
* A Construction Expert System For The Preliminary Design Of Reinforced Concrete Structures
* Automatic Pavement-Distress-Survey System
* Highway Pavement Surfaces Reconstruction by Moire Interferometry
* A Field Prototype of a Robotic Pavement Crack Sealing System
* A Design for Automated Pavement Crack Sealing
* Integration of Diverse Technologies for Pavement Sensing
* Force Feedback Excavator and Material Handling System
* Automated Pavement Crack Filler
* Perception and Control for Automated Pavement Crack Sealing

* Adaptive Control for Robotic Backhoe Excavation
* Subsurface Pavement Structure Inventory Using Ground Penetrating Radar and a Bore Hole Camera
* A Data Base Program for Preparing and Reporting Concrete Mix Designs
* Pavement Image Processing Using Neural Networks
* An Expert System For Construction Contract Claims
* Analysis and Generation of Pavement Distress Images Using Fractals
* Measuring Highway Inventory Features Using Stereoscopic Imaging System
* Using Geographic Information Systems For Highway Maintenance
* Simulation for Construction Planning and Control
* Automated Bridge Plans By Computer Aided Software
* Electronic Communication Between Project Participants
* CAD-Integrated Rebar Bending
* Knowledge Based Expert System for Construction Scheduling
* Pavement Design Using An Expert System
* A Database Approach for CAD/KBES Integration for Construction Planning
* Real-Time Project Tracking
* A Relational Database For Long-Span Highway Bridges
* A Construction Information Management System
* Surface Condition Expert System For Pavement Rehabilitation Planning
* Digital Imaging Concepts And Applications In Pavement Management
* An Expert System for Pavement Rehabilitation Decision Making
* An Expert System for Contractor Prequalification
* Generic Framework For Evaluation Of Multiple Construction Robots
* Framework for Construction Robot Fleet Management System
* A Pavement Management Information System for Evaluating Pavements and Setting Priorities for Maintenance
* Autonomous Robot Excavator
* Integrating Data Bases For Executing Automated Construction Tasks
* Computer Integration For Automated And Flexible Construction Systems
* Integrating Voice Recognition Systems with the Collection of Project Control Data
* Sensors And Expert Systems In Production Optimization Of Earthmoving Scrapers
* Control System Architecture for Unmanned Ground Vehicles
* Teleoperated Excavator
* A Graphical Interface For Curved Steel Girder Bridges
* An Expert System for Diagnosing and Repairing Cracks in Cast-in-Place Concrete Structures
* Probabilistic Scheduling in Tunneling
* A Database For Tunnel Planning And Estimating
* Kinematics and Trajectory Planning for Robotic Excavation

* Design Considerations For Automated Crack sealing Machinery
* A Computer System For Highway Bridge Rating And Fatigue Life Analysis
* Knowledge-Based Construction Scheduling
* A Hypertext Database for Asphalt Paving
* A Knowledge-Based Expert System for Quality Assurance of Concrete
* New Capability for Remote Controlled Excavation

There is focused research and development for automation/robotics applications for: military applications, building construction industry, and coal mining; a similar program for road construction, maintenance, and operations is now underway. In the near future, academic and industry symposia should be encouraged and organized for the presentation of research in this emerging technology. A community of participants and stakeholders in the technology should be nurtured and provided with an ongoing forum and network for the exchange of ideas and information. In addition to fomenting new technology and applications, this program can well serve to pioneer new relationships among industry, federal and local government, and academia.

EXAMPLES OF THE STATE-OF-THE-ART

The key automation/robotics technology subfields relevant to our area of interest include: robotics and intelligent control systems (including telerobotic, semi-autonomous, and autonomous systems); symbolic and connectionist processes (i.e., expert [or knowledge-based] systems, and neural networks); intelligent databases and program management systems; and intelligent sensor processing.

Robotics And Intelligent Control Systems

Within the known, well-defined confines of the construction site, autonomous robots are within the state-of-the-art. Machine vision is still rudimentary, but a robotic system can "know" its position and objects in its environment with assistance from external navigation beacons and other external aids, such as bar codes. Semi-autonomous or telerobotic robots are available for even sooner operational demonstrations. Until user confidence is established, and until legal liability issues are settled, robots on the job site are likely to be under human supervision, if not direct and continuous control.

The U.S. military - especially the Unmanned Ground Vehicle Joint Program Office (UGV JPO) - has been experimenting with an array of UGVs for various applications, but few are operational (and those are man-in-the-loop, telerobotic explosive ordnance disposal systems, which are relatively small vehicles). The technology for telerobotic and semi-autonomous platforms are well in hand, however. Man/machine interfaces include 3D displays, touch screen controls, and reconfigurable, digital graphics status indicators. Autonomous military UGVs have been demonstrated under limited environmental conditions, but there are commercially available autonomous robots for security patrol and indoor delivery applications. Relevant military UGV systems include: the attachable robotic convoy capability; autonomous rapid runway repair (ARRR); Haz-Trak; Pele remote control system; remotely controlled mobile excavator; remotely operated Bobcat; robotics for airbase recovery program; and telerobotic excavator.

ARRR

The autonomous rapid runway repair excavator, made by John Deere and modified by the Air Force, is over 30 feet long with the excavator arm extended. It is 10 feet wide and 10.5 feet tall. Locomotion is by a 6-wheel, all-terrain skid steer undercarriage and a 295 hp diesel engine. It weighs over 43,000 pounds, can lift nearly 8,700 pounds, and it can dig to a depth of 20 feet. The operator control station weighs 50 pounds. The ARRR carries stereo video cameras (including color and infrared), a laser scanner, a VME electronics interface for automotive functions, high-performance processor, inertial/GPS navigation system, modular end-effectors for a force-feedback arm. The control center can supervise 25 platforms simultaneously.

Haz-Trak

The *Haz-Trak* excavator and material handling system, made by John Deere and modified by Kraft TeleRobotics, uses bilateral force feedback to remotely control the hydraulically-powered, 7000-pound excavator. The technology can be scaled up to a 70 ton system. The current platform is nearly 8 feet high, about 5 feet wide, and 15.5 feet long (with the arm folded). Maximum dumping height is over 9 feet, with a maximum reach at ground level of 15 feet. Maximum digging depth is 8 feet 8 inches. One operator can control two *Haz-Trak* vehicles. The vehicle also has an hydraulically-actuated dozer blade which can be used for grading, backfilling, and leveling of the vehicle on sloped surfaces. The operator's viewing system includes two onboard, fixed, color cameras for peripheral vision, and a single pan and tilt-mounted color camera with auto iris, auto focus, and zoom capabilities. The operator control console has three video displays, a two-axis, fully proportional, displacement type joystick for control of vehicle speed and direction. A thumb-operated switch on the joystick controls the dozer blade. Another joystick provides closed loop control of the camera pan and tilt.

PELE

The *PELE* is a modular, universal, add-on kit which can be **adapted to any vehicle**, converting it into a remotely-controlled vehicle at a fraction of the cost of developing special-purpose telerobots. The conversion does not interfere with the vehicle's normal functions - it can be driven by an on-board driver in the usual way. The first vehicle equipped with the *PELE* was a main battle tank (MBT).

The *PELE* (meaning "miracle" or "wonder" in Hebrew) was developed by RAMTA, a subsidiary of Israel Aircraft Industries (IAI). RAMTA wanted to demonstrate the feasibility of an unmanned ground vehicle (UGV), with **semi-autonomous capability**, for countermine applications. A combat tank - or a construction vehicle - can become a teleoperated vehicle for a short duration and for specific operations, as required. After the specific operation is completed, the vehicle can resume its manned mode, if desired. The installation of the *PELE* system takes less than eight hours. Once the system is in place, the vehicle can be switched between manned and telerobotic modes in **less than a minute.**

The *PELE* consists of the following units: Operator Control Unit (OCU), a compact control subsystem which allows remote control from any convenient location, including another vehicle; Vehicle Units for control of platform functions; Inertial Navigation System to allow the vehicle to travel a path autonomously; and Electro-Mechanical End Actuators to manipulate physically the vehicle's control system. The remote control actuators include those for: pressing the accelerator pedal, steering, changing gears, engine start and shut down, excavator arm motion, dozer blade motion, and special-purpose operations.

The *PELE* currently uses a Radio Frequency (RF) link with a range of 3 km, but it can also use a fiber-optic link. The *PELE* has a video system (with a camera for driving and a camera for surveillance, target acquisition and aiming) to provide vision for the operator. *PELE* eases the burden on the operator with its **automatic functions.** The operator can concentrate on his job and not on driving. The autonomous modes, described below, are achieved by software and on-board processing, and complemented by a user-friendly OCU.

* **Automatic Driver**
The operator provides simple speed and directional commands and the *PELE* determines the engine torque, gear changes, etc. that are needed.

* **Automatic Heading**
The vehicle can maintain a selected heading automatically.

* **Automatic Navigation**
The vehicle can travel a path autonomously using pre-programmed navigation way-points. The path, which can be planned on a map, is presented to the operator. The operator can change the path by inserting new way-points at any time.

* **Follow-The-Camera**
This mode enables the operator to select a point in the video camera's field-of-view, set cross-hairs on it, and have the vehicle move toward that point without further operator intervention. Thus, the operator can "drive the camera" toward an object, instead of driving the vehicle directly.

* **Retrotraverse**
This mode will enable the vehicle to return to its starting point (or other designated location) if the communication link were lost, or as a way to reduce the operator's burden on a return trip. The vehicle's path will be stored in the on-board computer as it moves forward.

* **Manual Mode**
This is a back-up mode: the operator can control directly each and every actuator.

T-REX

The Transuranic Storage Area Remote Excavator (T-REX) is an electrically powered, front-shovel, teleoperated, tracked excavator being developed for the Department of Energy Idaho National Engineering Laboratory (INEL). It is a standard 95,000-lb front-shovel production excavator that has been modified for remote control to safely retrieve hazardous waste. It receives commands from a remote operator linked by fiber optic cable, and it provides video and command signal feedback to the operator. It has three cameras with pan, tilt, and zoom capability mounted on the excavator. A stereo camera pair mounted on the boom provides depth perception to the operator.

EL200B

Caterpillar has a telerobotic excavator (EL200B) and a telerobotic dozer available. Operating ranges are 5,000 ft. by radio link, and 1,000 ft. by coaxial cable link.

LUCIE

In the U.K., the Lancaster University Computerised Intelligent Excavator (LUCIE) has been demonstrated. The initial system focused on intelligent control of the excavator arm (and not vehicle movement), with the main task of trenching (to dig a flat-bottomed trench accurately to a depth input by the user).

LUCIE dug efficiently in varying ground conditions, including coping with obstructions such as boulders, without human interference. A conventional mini-excavator (JCB-801) was modified for the project. The control system included an expert system.

Robotech

Robotech Industries converted a Melroe Co. Bobcat into a remote controlled system with a manipulator arm and 3D vision. It weighs 4,730 pounds, is 5.5 feet tall, 10 feet long, and 4.25 feet wide. It can carry a payload of 1,400 pounds. A radio control link operates the remote Bobcat to a distance of 300 feet, but it can be upgraded to 5,000 feet. The operator control unit uses a joystick controller and video monitor.

NIST RCS

A control system which is being used widely for the control of military robots (as well as the robotic excavator research at the University of North Carolina) is the National Institute of Standards and Technology (NIST) Hierarchical Real-time Control System (RCS), which had its origins in early work by J. Albus on neurophysiological models and adaptive neural networks. The Hierarchical RCS architecture is a generic framework in which to place, connect, and activate the intelligence of robotic systems. The RCS, designed originally for industrial robots, is a mechanism by which sensors, expert systems, data bases, computer models, and machine controls may be linked and operated such that the system behaves as if it were intelligent. Recently, the RCS has been modified and adapted for use aboard autonomous intelligent vehicles, including the Multiple Autonomous Underwater Vehicle (MAUV) and the Tech-based Enhancement for Autonomous Machines (TEAM) land vehicle project. The RCS is also the reference architecture for the telerobotic system developed for the NASA space station, and is being used in coal mining robots.

The RCS can perform complex real-time tasks in the presence of sensory or other information input. It can decompose high-level goals into low-level actions, making real-time decisions in the presence of noise and conflicting demand for resources. It provides a framework for linking artificial intelligence techniques with real-time control in a rapidly changing environment. The RCS interfaces sensors or incoming information to controls through a hierarchically-structured, real-time, world model. The world model integrates current data with a priori knowledge to provide the control system with a current best estimate of the state of the world.

The RCS may be decomposed into several hierarchical levels (typically six to eight levels). Each control level receives input commands from a higher level (or in the case of the top level, from outside the system), sensory (or other information) feedback, and status feedback from the next lower control level. Each control level provides output commands to the next lower level and status reports to the next higher level. Each level receives appropriate sensory data, making it a sensory interactive control architecture.

The hierarchical structure of the RCS permits complex processes to be decomposed into simpler tasks - just as in human organizations. In general, hierarchical structures resemble pyramids, with each level subordinate to those above, a partially-ordered structure of entities in which every entity but one is successor to at least one other entity; and every entity except the basic entity is a predecessor to at least one other entity. A formal hierarchy is a complex system in which each subsystem is subordinated by an authority relationship to the system to which it belongs.

The real-time ability of the RCS is essential for robotic control - a robot (like a person) does not have the leisure to contemplate (or calculate off-line) if it were about to smash into a wall or fall into a hole. Likewise, a robotic control system must operate in real-time to deal effectively with the temporally and spatially on-rushing events.

CARL

The North Carolina State University Construction Automation & Robotics Laboratory (CARL) is developing a multipurpose robotic manipulator system to serve as an experimental device. It has been designed for digging, welding, and lifting, with various optional end effectors, such as buckets and grippers. Adaptive control for robotic backhoe excavation is also under development. The adaptive, hierarchical planning and control software is needed so the autonomous excavator can manipulate large removable obstacles, such as rocks. Three accelerometers and a load cell on the gooseneck boom are used to detect and identify an obstacle. A decision tree responds to the obstacle based on whether the obstacle is small, medium, or large (within defined criteria). (CARL is also examining robotic systems for automatic rebar bending).

Pavement Crack Sealers

Prototypes of pavement crack sealing robots have been developed, and analysis indicates that this is a highly cost/effective application of construction robotics. Various telerobotic configurations are being explored. The control system: acquires sensor data and develops a representation of the pavement surface; maps the cracks to be filled; develops a work plan; executes the blowing and sealing operations; repeats the above steps.

Site Positioning System

Virginia Polytechnic Institute is performing research on a three-dimensional real-time positioning system for construction surveying and on-site autonomous robotic vehicle control. The system uses lasers and GPS, and it can provide accuracies within 10 mm for sites 400 x 400 meters, with 10 readings/second.

CALTRANS

The California Department of Transportation (CALTRANS) has been developing robots to perform highway maintenance functions, including: delineation and signing (automated raised marker placement, paintstriping guidance and information systems, automated graffiti removal); hazmat debris and litter removal (remote hazmat vehicle, litter bag retrieval, automated litter pickup); landscape management (smart herbicide applicator, remote controlled irrigation management system); workzone safety (smart highway safety cones, workzone warning devices); pavement integrity (automated crack/joint sealing machine, automated pothole filling machine); structures maintenance (telerobotics, maintenance minded infrastructure, unmanned hovercraft for inspection).

Building Construction Robots

In the building construction industry, robots are under development for the following functions: spraying concrete for tunnel liner; finishing surface of cast-in-place concrete; placing concrete in horizontal slabs; vibrating cast-in-place concrete; carrying concrete from batching plant to cable crane; fireproofing spraying; paint spraying; erecting structural steel beams and columns; placing reinforced steel; wrapping existing structures with carbon steel; welding; inspecting reinforced concrete walls; inspecting facade; inspecting bridge structural surface; collecting and analyzing data for controlling tunneling machine; excavating earth; assembling wall liner segments in sewer and power tunnels; inspecting and monitoring particles in air; hot resurfacing on highways; picking and distributing construction materials.

Intelligent Sensor Processing

Much of the work in machine vision and image processing for highway applications has focused, so far, primarily on pavement evaluation. Substantial progress has been made, in the U.S., Japan, and Europe, in developing automated systems (sensors, processors, and software algorithms) for distress-data acquisition and interpretation.

For example, a Japanese automatic pavement-distress survey system uses laser, video, and image processing, carried on a survey vehicle, to measure cracking, rutting, and longitudinal profile simultaneously, without contact, accurately and rapidly, while moving at 60 km/hr. The system measures cracks over 1 mm wide and can evaluate parameters based on crack length, width, direction, position, and quantity. Output data from the system can be formatted automatically for the pavement data bank. The system can perform automatic crack recognition with human ability by using a line-finding algorithm that can extract a crack in a noisy environment. The algorithm, implemented in high-speed processors, analyzes projection curves.

A U.S. system, the *Pavement Distress Imager*, can survey pavement condition at highway speeds using four charge coupled device (CCD) video line cameras and a pipe line image processor which processes the images in real-time. The system can obtain a line image every 0.1 inch longitudinally, with a transverse resolution of 0.05 inches. The image processor, for example, can process a four-foot width of pavement with a line image of 512 pixels, with one bit per pixel. There are 10,560 line images generated per second. This multiplies to 5,406,720 bits/second. The output is filtered because the amount of information and flow rate is too high for existing mass storage devices (digital tape is used). Holographic memory should be suitable for this type of data storage (with 100 gigabyte storage capacity and a transfer rate of 1 terabyte/sec). In other research, fractal techniques have been used to compress data and alleviate the data storage limitations. A crack is represented as a fractal curve, represented by only one or a few numbers. Using the compressed data, realistic crack images must later be reconstructed from the fractal crack parameters.

Another example pavement distress image processing system, the *Automated Road Image Analyzer*, can automatically recognize and quantify alligator cracks, longitudinal cracks (single or multiple, sealed or not sealed), and lateral/transverse cracks (single or multiple, sealed or not sealed). The minimum size of detectable crack is about 1.6 to 3.1 mm. The system creates an automatic database which automatically identifies the location of pavement distress as it reads each video frame.

Research is ongoing for the detection of thin cracks on noisy pavement images. Techniques include: increasing video resolution from higher-resolution cameras or Super VHS tapes; applying a low pass filter to remove pixels with rapid intensity variations; using a localized edge detector; or using an edge detector based on the Sobel operation coupled with Kittler's automatic thresholding and a sequence of post-processing operations.

To enhance performance, computer simulation and modeling have been used to optimize lighting for pavement evaluation systems, to examine performance as a function of lighting, crack geometry, and reflectivities. Also, sensor integration (of video and lasers, for example) can improve the automated identification of pavement cracks and the gathering of good pavement data.

Various military programs have been developing image processing systems for machine vision in unmanned ground vehicles, to allow the vehicles to move about autonomously. Machine vision is still rudimentary, but it may be sufficient for many road construction and maintenance functions (such as excavation or scraping).

Bar code technology is being developed for: material control, inventory, and maintenance; tool, equipment, and consumable material issue; timekeeping and cost engineering; purchasing and accounting; document control and office operations. In particular, knowing what and where everything is on a job site would be a valuable capability. Laser scanners can read the bar codes. Equipment on site can also be located using video or radio location systems, where detectors are erected about the site.

Research on sensor processing for automated coal mining systems is relevant to road construction applications. Position and heading can be determined using laser, inertial (gyroscope), gravitational (clinometer), and magnetic (compass) sensors. An external laser-based position and yaw determination system can be used in conjunction with onboard sensors to provide more reliable (because of redundancy), more consistent sensor system. The onboard gyroscope provides heading information, fluxgate compasses (two) provide heading with respect to north, and clinometers give platform pitch and roll information. The laser system includes: laser scanners, retroreflective targets, sensor communication network, host computer hardware, position and heading computation module, and platform control module. The system maintains a 0.15 degree target angular position accuracy over most of the 21 ft. range and 105 degree angular field of view of the sensor. Accuracy in tracking the position and heading of the platform were 0.25 deg. in heading and 2.59 in. in position.

Mining research has applied adaptive signal discrimination to vibrational coal interface detection, so the system can discriminate between coal and surrounding rock waste. Accelerometers, geophones, and piezoelectric films are mounted on the mining machines and, with a computer and signal processing software, they are used to monitor and analyze vibrations generated during mining operations. Another coal interface detection system under investigation uses a passive infrared system to measure temperature changes associated with the cutting of coal and adjacent strata. Yet another interface detection system uses a doppler radar in conjunction with signal processing. Comparable systems might be useful in road construction for excavation operations.

Sensors well-established for autonomous vehicle navigation, guidance, and control include: global positioning system (GPS), various types of inertial guidance systems (mechanical gyroscopes, laser gyros, fiber optic gyros), wheel sensors, radio and laser navigation systems, etc. The optimum system for road construction, maintenance, and operations will depend on the specific system and application.

Voice sensing (voice recognition/understanding) technology is sufficient for some applications in person/machine interfaces for machine control and project control data collection. Voice recognition chips are now available for a few dollars each. There has been some research for construction industry applications.

Symbolic And Connectionist Processes

There are numerous expert systems and neural networks under development relevant to many road construction and maintenance functions, including project planning, construction design and scheduling, bridge design and analysis, quality assurance, and pavement condition, among other applications.

Knowledge-based expert systems and neural networks are being developed to characterize quantitatively the condition of pavements based on the analysis of sensor measurements (such as image processing). An expert system would accept from a neural network input concerning the type, extent, severity of structural distress, as well as other pertinent characteristics, and then access historical records from a database concerning deterioration rates, design details, climatic factors, etc. The expert system would then apply its equivalent of human expertise and reasoning (in the form of rules) to determine structural adequacy, expected life and reliability, and suitable rehabilitation, repair, and maintenance strategies.

In Germany, an integrated pavement management system is being developed. The system will perform a survey (machine vision inspection) of the road surface; evaluate the condition of the pavement (i.e., determine the value of a condition index based on defined criteria); compare the ascertained condition with given quality requirements (normal, critical, inadequate); determine the priorities of necessary maintenance measures, or immediate intervention using traffic management; plan maintenance measures; execute maintenance measures.

U.S. programs are also integrating technologies (machine vision, processing techniques, etc.) for pavement sensing and evaluation. A pavement surfaces model, for example, contains a representation of surfaces, a description of surfaces, and a characterization process (consisting of filtering, reduction, fusion, and structuring operations on data). The model makes use of quadtrees to represent surface features: it serves as a framework which accepts sensor data and can output information, decisions, or automated actions. Another expert system is being developed for pavement design. Significant factors in developing the thickness design methodology for the base, subbase, and surface layer of rigid pavements include: load function; layer characteristics; modulus of rupture; design serviceability loss; reliability; and drainage coefficient.

An expert system called *SCEPTRE* has been used for pavement rehabilitation planning. The evaluation of a pavement segment's condition considers the pavement's functional and structural performance in terms of: ride quality, safety, surface distress, and structural adequacy. There are various response strategies, including: do nothing; fill cracks; fog seal; friction course; chip seal; double chip seal; thin asphalt concrete overlay; medium concrete asphalt overlay; thick asphalt concrete overlay; mill and replace. The decision analysis includes cost/effectiveness; type of surface distress; amount of surface distress; severity of surface distress; existing pavement performance (rate of deterioration); traffic levels; and climate.

A microcomputer-based expert system, having 300 heuristic rules as well as algorithmic programs, was developed for the maintenance and rehabilitation of flexible pavements on low volume roads. Input parameters include ride quality, structural condition, and performance. The system generates a set of maintenance or rehabilitation strategies by evaluating the overall pavement condition and determining the set of probable deteriorating causes.

A knowledge-based expert system is being developed for quality assurance of concrete at the construction site. It can run on a microcomputer. Its main purpose is to help users identify problems causing deterioration in the quality of concrete, but it can also be used to calculate the compressive strength of concrete for a specified concrete strength, or select the proportions of a normal weight concrete mix, or predict the values of slump, air content, and 28-day compressive strength on the basis of known quantities of constituent materials for normal weight concrete. Another expert system can be used for the preliminary design of reinforced concrete structures. Yet another expert system is being developed for diagnosing and repairing cracks in cast-in-place concrete structures.

Expert systems and computer-aided design are being integrated to improve construction planning. One such system, *Know-Plan*, can automatically generate construction plans. It has six modules for: 3D modeling, knowledge and data storage and manipulation, dynamic sequencing, interactive sequence modification, conventional scheduling, and visual simulation. Another expert system, *X-Pert*, was developed for construction scheduling. Yet another expert system, *AVOIDS* (Visually Oriented Intelligent Decision Support system), is being developed for construction coordination. It will provide a visually-oriented project coordination language common to the entire project team. It will provide team members with easy access to important project information, with access to information through hypertext-like links. Information types can be CAD models, graphics, database reports, text files, spreadsheets, computer images, video images, etc. Coordination is achieved through a coordination base model knowledge base and an inference engine. Another expert system is being developed for generating construction schedules, incorporating a subset of the acquired knowledge using object-oriented and rule-based approaches. The different modules that contain the knowledge interact via a blackboard architecture.

Expert systems have been developed for construction contracting. One system is used for contractor prequalification, which is a process of determining a candidate contractor's competence. Another expert system, for construction contract claims (CGS - Claims Guidance System), was developed at the U.S. Army Construction Engineering Research Laboratory. It includes such issues as: final payment, notice requirement, prejudice to government, government action, contract provision type, acceptable and prudent assumptions. The CGS could be modified for use by the FHWA for road construction.

An expert system developed to evaluate final covers for hazardous waste landfills might be modified for use in road construction (especially for medians or earth hills at the roadside). It includes rules concerned with subsidence, erosion potential, layer interactions, drainage, water migration, cover design, etc.

The *Kentucky Bridge Analysis System* (KYBAS) is a framework of interacting expert systems for the structural analysis and design of highway bridges. Another expert system is being developed for bridge monitoring, i.e., to use the dynamic response from normal vehicle loading to provide an early warning system of collapse. Yet another expert system, the *Bridge Fatigue Investigator* (BFI) is being developed to evaluate bridge fatigue. The BFI suggests where to inspect for fatigue damage, how severe the damage is, and the alternatives to be considered.

For construction equipment applications, *CRANE* is an expert system for optimal tower crane selection and placement on the construction site. An expert system, in conjunction with sensors, is being developed for the push-loaded earthmoving scraper. The objective is to obtain optimum production for a fleet of scrapers and pushers. Another expert system is being interfaced to a simulation package to create an integrated system for planning and analyzing earthmoving operations. The system chooses the optimum earthmoving system from several alternatives; then the simulation module uses the data provided by the expert system and the user to model and analyze the operation. Parameters considered in selecting the most appropriate equipment include: haul distance; material type (tough soil or rock, or soft soil); rock size; haul road conditions; underfoot conditions; and adverse grades. The system selects one or more of: scraper, bulldozer, truck-shovel combination. Another expert system is used to plan and control earthmoving operations with a larger set of equipment. The integrated simulator steps include: definition of distance and slope between cut and fill area; calculation of travel times (cycletimes) for hauling equipment; simulating daily production (considering operating factors and breaks); calculating the duration for one section (considering shrink and swell factors and quantitative constraints in the cut and fill areas); move to the next section in either the cost or the fill area, or both.

Expert systems have been developed for the diagnostic maintenance of coal mining systems. Similar systems could be designed for diagnostic maintenance of road construction and maintenance vehicles.

An expert system has been developed for process planning for automated stone cutting. The system has expert knowledge about fabrication techniques and an understanding about which resources can be used interchangeably for executing different tasks.

Intelligent Databases And Program Management Systems

There is some overlap in this category with expert systems applications, but the techniques are generally different from rule-based systems. For example, research is being conducted on object-oriented programming (OOP) for robotic excavation. The OOP is used for rapid prototyping of software, in this case for force-cognitive excavation (i.e., the control of a digging process in response to forces that develop between the excavator and the soil. Another OOP data module and knowledge-based construction management modules is being developed for integrating design, construction scheduling, and cost estimating.

An OOP is being used for warranting roadside safety hardware (guard rails, bridge rails, crash cushions, etc.). An OOP simulation system has been designed to integrate specific construction knowledge into construction process planning (which involves the selection of construction methods and the allocation of resources to achieve certain field operations while satisfying process constraints such as production, soil condition, and resource availability. *SEACONS* (SEAbee CONstruction Simulation) is another simulation for construction planning and control. It can be adapted for FHWA highway applications.

There is an integrated airfield pavement management system (IAPMS) in use which combines pavement engineering, database, forecasting, and budgeting tools in a comprehensive, interactive system for the planning and management of airfield pavement maintenance and rehabilitation. The IAPMS could be adapted for road pavement maintenance and rehabilitation applications.

There is a database program for preparing and reporting concrete mix designs. Functions include: selection of design mix parameters, design of concrete mix, viewing and reporting mix designs. Another database is designed for tunnel planning and estimating, to collect and organize tunnel construction data.

There are studies of automated construction work packaging systems, especially data modeling and knowledge representation.

COMEDI (COncurrently Multi-modal Engineering Database Interface) aids engineering interactions with database management systems by providing: multiple modes of query formulation which are simultaneously available; various query formulation modes contributing to the formulation of a single query; each mode updating its query formulation information to correspond to query components entered in other modes; output and correction options after query is formulated.

A database has been designed for seismic evaluation of the San Francisco Bay Bridge. A relational database was developed for long-span highway bridges, with information on about 200 long-span arch, cable-stayed, suspension, girder, and truss bridges. Information on each bridge includes: general substructure; superstructure; bid; construction; cost; performance; and rehabilitation/reconstruction aspects. The New Mexico Sate Highway Department is implementing computer aided software designed to automate bridge plans. New software has been developed for highway bridge rating and fatigue life analysis.

A computer aided rigging design system has been developed. The first version of the software performs initial crane equipment selection, sizing, and analysis for specific heavy lifts, and it checks rigging plans developed by other groups.

There are microcomputer programs used for heavy construction equipment productivity and cost evaluation. The programs: select the most productive equipment for a job (including earthmoving operations for highway construction) and ranking equipment by productivity rate and cost; estimate the unit cost or bid price for work produced by each equipment selected, or for any other equipment specified by the user; provide analysis of the bidding history and actual costs of previous jobs to allow the estimator to benefit from previous experience. Output includes: the type, code, capacity, and production of each equipment selected; the volume of earth moved for each section of the project; unit cost of the operation; total cost of the job. The user can input, from a menu, project conditions such as: management conditions, operators skills, job demands, size of project, type of soil or rocks, depths of cut, angles of swings, haul roads description, job accessibility, cost and type of fuel used, weather, wages, overhead, and profit rates. Equipment analyzed includes: draglines, power shovels, backhoes, hydraulic shovels, wheel front-end loaders, crawler front-end loaders, motorized scrapers, towed scrapers, wheel bulldozers, crawler bulldozers, highway trucks, and off-highway trucks. There is another computer assisted system for construction robot implementation logistics, to assist a construction firm in robot assignment scheduling. The prototype software was developed in Hypercard and QuickBasic on the Apple Macintosh microcomputer. The military is also developing a computer-aided technique for planning, designing, estimating, and scheduling for horizontal construction, including earthmoving.

An intelligent, distributed database management system, in conjunction with a traffic engineering knowledge-base system, is being developed for signal maintenance. The database includes: intersection geometric data, intersection traffic volume, traffic signal control hardware, arterial signal timing plan, intersection signal timing, intersection hardware maintenance, maintenance schedule record, and accident reports.

Hypertext is a database with active cross references and it allows users to jump to other parts of the database as desired. A hypertext database was developed for the construction inspection of asphalt paving.

A real-time project tracking system is being designed. The system charges costs, manhours, and quantities of work in place at the time it occurs, and it includes a detailed work breakdown structure. Data is transferred from the field into the system in near real-time. Field data entry can be via digitizer template, bar coding, or voice recognition.

Geographic information systems are being considered for use in pavement management systems and sign management systems. The pavement management system includes information on: pavement types, functional classification of the highway, types of rehabilitations, costs, and pavement condition evaluation. The sign management system includes such information as: sign location, video freeze picture with message and environmental context, costs, work order generation.

SUMMARY

The technology of automation/robotics for road construction, maintenance, and operations is ripe. Many systems are under development in many places. Virtually all of the necessary road construction/maintenance functions can be aided by automation or robotics. Few systems, however, are operational. Previous research and development, such as accomplished by the military or building construction industry, can be profitably leveraged by the FHWA in its automation/robotics development program. Demonstrations of useful, cost/effective automation/robotics for road construction, maintenance, and operations, using modified systems from other government agencies, private industry, and academia, can be performed within one or two years.

Addco Manufacturing Co., Literature, St. Paul, Minnesota, 1990

AEC, Expert, Construction
Finn, Gavin A., "AEC Experience With Expert Systems In Construction," Excellance In The Construction Project: Proceedings Of Construction Congress I, ASCE, San Francisco, CA, March 5-8, 1989

Algorithm, Mechanical Assembly
Homem de Mello, L. S. and Sanderson, A. C., "A Correct and Complete Algorithm for the Generation of Mechanical Assembly Sequences," IEEE Transactions on Robotics and Automation, vol. 7, no. 2, pp. 228-240, April 1991

Algorithm, Path Planning, d-dimensions
Krishnan, S. S. and Sanderson, A. C., "The Generalized Window Corner Algorithm for Path Planning in d-dimensions," submitted to 1993 IEEE International Conference on Robotics and Automation

Algorithm, Real-Time, Mining Machine
Huang, Hui-Min, et. al., "Task decomposition and Algorithm Development for Real-Time Motion Control of a Continuous Mining Machine," NISTIR 4596, May 1991

Algorithms, Pavement
Koutsopoulos, Harris N. and Ibrahim El Sanhouri, "Methods and Algorithms for Automated Analysis of Pavement Images," Transportation Research Board 70th Annual Meeting, Washington, DC, January 13-17, 1991

ARIA, Pavement, Image Processing
Mohajeri, Jerry H. and Patrick J. Manning, "ARIA: An Operating System of Pavement Distress Diagnosis by Image Processing," Transportation Research Board 70th Annual Meeting, Washington, DC, January 13-17, 1991

Artificial Intelligence, Earthmoving Operations
Bernold, Leonhard E., "Low Level Artificial Intelligence And Computer Simulation To Plan And Control Earthmoving Operations," Earthmoving And Heavy Equipment: Proceedings Of The Conference Sponsored By The Committee On Construction Equipment And Techniques, ASCE, Tempe, AZ, February 5-7, 1986

Asphalt, Finisher
Goto, F. and Saitoh, T., "Development of Advanced Asphalt Finisher," Proceedings of 9th International Symposium on Automation and Robotics in Construction, Tokyo, Japan, June 1992

Assembly Plans, Geometric Approach
Hocaoglu, C. and Sanderson, A. C., "Evaluation and Selection of Assembly Plans: A Geometric Approach," Submitted to 1993 IEEE International Conference on Robotics and Automation

Assembly
Sanderson, A. C., Homem de Mello, L. S., and Zhang, H., "Assembly Sequence Planning," AI Magazine, 1990.

Assembly Tasks, Assembly Time
Homem de Mello, L. S. and Sanderson, A. C., "Two Criteria for the Selection of Assembly Plans: Maximizing the Flexibility of Sequencing the Assembly Tasks and Minimizing the Assembly Time Through Parallel Execution of Assembly Tasks," IEEE Transactions on Robotics and Automation, vol. 7, no. 5, October 1991

Automated
Kuzela, Lad, "Here Comes The Automated Manager," Industry Week, Nov. 20, 1989, pp. 45-46

Automated
Velinsky, Steve, "Progress on Automated Joint Sealing," presented at 72nd Annual Meeting of Transportation Research Board, Washington, D.C., January 1993

Automated
Ward, Carter J., "High Speed Multi-Link Automated Control," Excellance In The Construction Project: Proceedings Of Construction Congress I, ASCE, San Francisco, CA, March 5-8, 1989

Automated, Asphalt, Pavement
Pagdadis, Sotiris, "Automated Hot in-Place Recycling of Asphalt Pavements," Presented at 72nd Annual Meeting of Transportation Research Board, Washington, D.C., January 1993

Automated, Bar Fastening, Bridge Decks
Martinelli, David R., Abraham, John and Stobbe, Terrance, "Technical and Economic Feasibility of Automated Reinforcement Bar Fastening on Bridge Decks," presented at 72nd Annual Meeting of Transportation Research Board, Washington, D.C., January 1993

Automated, Bridge, Computer
McCarthy, William C. and Kenneth R. White, "Automated Bridge Plans By Computer Aided Software," Computing in Civil Engineering: Microcomputers to Supercomputers, Proceedings of the Fifth Conference, Alexandria, VA, American Society of Civil Engineers, March 29-31, 1988

Automated, Construction, Data Modeling
Kim, Jae-Jun and C. William Ibbs, "Toward the Automated Construction Work Packaging: Data Modeling and Knowledge Representation Issues," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Automated, Crack Sealing Machinery
Velinsky, Steven A. and Kenneth R. Kirschke, "Design Considerations For Automated Crack Sealing Machinery," Applications of Advanced Technologies in Transportation Engineering, Proceedings of the Second International Conference, American Society of Civil Engineers, New York, 1991

Automated, Pavement
Haas, Carl, et. al., "A Design for Automated Pavement Crack Sealing," Preparing For Construction In The 21st Century, Proceedings Of Construction Congress '91, ASCE, Cambridge, MA, April 13-16, 1991

Automated, Pavement
Hendrickson, Chris and Sue McNeil, "Automated Pavement Crack Filler," Data Sheet, carnegie Mellon U., Pittsburgh, PA, 1992

Automated, Pavement
Hendrickson, Chris, et. al., "Perception and Control for Automated Pavement Crack Sealing," Applications of Advanced Technologies in Transportation Engineering, Proceedings of the Second International Conference, American Society of Civil Engineers, New York, 1991

Automated, Pavement
Mendelsohn, David H., "Automated Pavement Crack Detection: An Assessment of Leading Technologies," In North American Pavement Management Conference, 1987

Automated, Pavement
Ritchie, Stephen G., et. al., "Development of an Intelligent System for Automated Pavement Evaluation," Transportation Research Board 70th Annual Meeting, Washington, DC, January 13-17, 1991

Automated, Pavement, Equipment
Proceedings for the Automated Pavement Distress Data Collection Equipment Seminar, Iowa State University, Ames, Iowa, June 12-15, 1990

Automated, Pavement, Surface, Distress, Evaluation
El-Korchi, Tahar, et. al., "System design for Automated Pavement Surface Distress Evaluation," Transportation Research Board 70th Annual Meeting, Washington, DC, January 13-17, 1991

Automated, Road Maintenance
Hsieh, Ting-ya and Carl Haas, "Costs and Benefits of Automated Road Maintenance," presented at 72nd Annual Meeting of Transportation Research Board, Washington, DC, January 1993

Automated, Road Maintenance
Hsieh, Ting-ya and Carl T. Haas, "Costs and Benefits of Automated Road Maintenance," Dept. of Civil Engineering, University of Texas at Austin, November 1992

Automatic Leveling, Road, Construction
Ulrich, A., "Automatic Leveling in Road Construction," Proceedings of 8th International Symposium on Automation and Robotics in Construction, Stuttgart, Germany, June 1991
Automatic Road Analyzer, Mobile Data Acquisition Vehicle Highway Products International, Inc., Automatic Road Analyzer - Mobile Data Acquisition Vehicle, Product Bulletin, 1985

Automatic, Pavement, Distress, Survey
Fukuhara, Toshihiko, et. al., "Automatic Pavement-Distress-Survey System," Journal of Transportation Engineering, Vol. 116, No. 3, May/June 1990, pp. 280-286

Automation
Brazell, James W., "Automation Of A Truck-Mounted Drill Rig," Preparing For Construction In The 21st Century, Proceedings Of Construction Congress '91, ASCE, Cambridge, MA, April 13-16, 1991

Automation
Wong, Thomas C.K. and Denis A. Chamberlain, "Essential Factors in the Automation of Tall Building Inspection," 9th International Symposium on Automation and Robotics in Construction, Tokyo, Japan, June 3-5, 1992

Automation, Construction
Bernold, Leonhard E., et. al., "Emulation For Control System Analysis In Automation Construction," Journal of Computing in Civil Engineering, Vol. 3, No. 4, October 1989, pp. 320-332

Automation, Pavement
Haas, Carl, et. al., "Opportunities For Automation In Pavement Maintenance," Transportation Association of Canada Annual Conference, Winnipeg, Manitoba, September 15-19, 1991

Automation, Pavement
Haas, Carl, Shen, Helen, Phang, William A. and Haas, Ralph, "An Expert System for Automation of Pavement Condition Inventory Data," In North American Pavement Management Conference, 1985

Automation, Pavement
McNeil, Sue, "An Analysis of the Costs and Impacts of the Automation of Pavement Crack Sealing," Carnegie Mellon U., Pittsburgh, PA, 1992

Automation, Robotics
Bernold, Leonhard E., "Automation And Robotics In Construction: A Challenge And A Chance For An Industry In Transition," Project Management, Vol. 5, No. 3, August 1987, pp. 155-160

Automation, Robotic, Construction
Killen, Timothy S., "Automation and Robotic Applications in North American Construction," Cost Engineering, Vol. 33, No. 7, July 1991, pp. 9-13

Automation, Robotics, Mining
Welsh, Jeffery, "Automation and Robotics Technology for Intelligent Mining Systems," NASA Conference on Space Telerobotics, Pasadena, CA, Jan. 31 - Feb. 2, 1989

Automation, Robotics, Road, Construction, Maintenance
Skibniewski, Miroslaw and Hendrickson, C., "Automation and Robotics for Road Construction and Maintenance," Journal of Transportation Engineering, Vol. 116, No. 3, May/June 1990, pp. 261-271

Automation, Site
Baecher, Gregory B., et. al., "Integrated Automation for Site Work," Excellance In The Construction Project: Proceedings Of Construction Congress I, ASCE, San Francisco, CA, March 5-8, 1989

Automation, Snowplow
Fukuda, N., et al., "Automation of Snowplow," Proceedings of 9th International Symposium on Automation and Robotics in Construction, Tokyo, Japan, June 1992

Bar Code, Construction
Bell, Lansford C. and Bob G. McCullouch, "Bar Code Applications in Construction," Journal of Construction Engineering and Management, Vol. 114, No. 2, June 1988, pp. 263-278

Bar Code, Equipment, Materials Tracking, Construction
Bernold, Leonhard E., "Bar Code-Driven Equipment And Materials Tracking For Construction," Journal of Computing in Civil Engineering, Vol. 4, No. 4, October 1990, pp. 381-395

Bar-Code Technology, Construction
Bernold, Leonhard E., "Testing Bar-Code Technology In Construction Environment," Journal of Construction Engineering and Management, Vol. 116, No. 4, December 1990, pp. 643-655

Bridge Deck, Radar
Maser, Kenneth R. and Rawson Alan, "Network Bridge Deck Surveys Using High Speed Radar: Case Studies of 44 Cracks," In Proceedings of the Transportation Research Board, Number 920751, 1992

Bridge Monitoring
DeWolf, J., et. al., "Expert Systems for Bridge Monitoring," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Bridge, Robot
McCrea, A. and Chamberlain, D., "Towards the Development of a Bridge Inspection Robot," Proceedings of 10th International Symposium on Automation and Robotics in Construction, Houston, May 1993

Bridges, WSPRO
Arneson, L.A., Shearman, J.O., Jones, J.S., "Evaluating Scour at Bridges Using WSPRO", Proceedings of the Transportation Research Board, Number 920617, 1992

CAD-Integrated, Rebar Bending
Miltenberger, Matthew A. and Leonhard E. Bernold, "CAD-Integrated Rebar Bending," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

CADD, Database
Pollak, Axel and Rosalind Pierce-Spring, "CADD - Database Application for Facility Inspections," Applications of Advanced Technologies in Transportation Engineering, Proceedings of the Second International Conference, American Society of Civil Engineers, New York, 1991

CAT 245 Hydraulic Hoe
Lewis, Chris R. and Cliff J. Schexnayder, "Production Analysis Of The CAT 245 Hydraulic Hoe," Earthmoving And Heavy Equipment: Proceedings Of The Conference Sponsored By The Committee On Construction Equipment And Techniques, ASCE, Tempe, AZ, February 5-7, 1986

CIMS, Construction
Rasdorf, William J. and Mark J. Herbert, "CIMS: A Construction Information Management System," Computing in Civil Engineering: Microcomputers to Supercomputers, Proceedings of the Fifth Conference, Alexandria, VA, American Society of Civil Engineers, March 29-31, 1988

Civil Engineering
Scarponcini, Paul, et. al., "Information Follows Function," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Civil Engineering
Setting A National Research Agenda For The Civil Engineering Profession: Executive Summary, Civil Engineering Research Foundation, Report #91-F1003.E, September 1991

Civil Engineering
Setting A National Research Agenda For The Civil Engineering Profession: Vol. 1, Final Report, Civil Engineering Research Foundation, Report #91-F1003, September 1991

Coal Mining, Automation
Schnakenberg, George H. Jr., "U.S. Bureau of Mines Coal Mining Automation - Research Update," Mining Automation, 4th Canadian Symposium, Saskatoon, Canada, 16-18 Sept. 1990

Coal Mining, Automation, Hierarchical Real-Time
Huang, Hui-Min and Richard Quintero, "Task Decomposition for the Design of a Coal Mining Automation Hierarchical Real-Time Control System," NIST

COMEDI, Database
Howard, Cynthia Stotts and H. Craig Howard, "COMEDI: A Multi-Modal Database Interface," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Computer Aided, Rigging Design System
Bohinsky, Joseph A. and Douglas W. Falls, "Computer Aided Rigging Design System," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Computer Assisted, Construction, Robot
Cornejo, Carlos, et. al., "Computer Assisted System For Construction Robot Implementation Logistics," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Computer, Automated, Construction
Singh, Amarjit, "Computer Integration For Automated And Flexible Construction Systems," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Computer, Concrete, Bridges
Farran, H.J., "Implementation of the Computer Analysis of Segmentally Erected Prestressed Concrete Bridges," Computing in Civil Engineering: Microcomputers to Supercomputers, Proceedings of the Fifth Conference, Alexandria, VA, American Society of Civil Engineers, March 29-31, 1988

Computer, Highway, Bridge
Wang, Ton-Lo, "A Computer System For Highway Bridge Rating And Fatigue Life Analysis," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Computer, Robotic
Rihani, Rami A. and Leonhard E. Bernold, "Computer Integration for Robotic Masonry," Submitted to the Journal Microcomputers in Civil Engineering," September 1992

Computer, Visual, Teleoperated Robotics
Mallem, M., Chavand, F., Colle, E., "Computer-Assisted Visual Perception in Teleoperated Robotics," Robotica (1992) Volume 10, pp. 93-103, 1991

Computer-Aided, Engineering
Sammarco, John, "Computer-Aided Software Engineering (CASE) for Software Automation," U.S. Bureau of Mines, IC 9265, 1990

Computer-Assisted, Coal Mining
Schnakemberg, George H. Jr., "Computer-Assisted Continuous Coal Mining System-Research Program Overview," U.S. Bureau of Mines, IC 9227, 1989

Computer-Based
Syal, M.G., et. al., "Computer-Based Integration Of Design And Project Controls," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Computer-based
Tokar, Michael D., "Utilizing On-Site Computer-Based Information Systems," Excellance In The Construction Project: Proceedings Of Construction Congress I, ASCE, San Francisco, CA, March 5-8, 1989

Computer-Controlled
Bernold, Leonhard E., et. al., "Computer-Controlled Brick Masonry," Journal of Computing in Civil Engineering, Vol. 6, No. 2, April 1992, pp. 147-160

Computer-Integrated, Construction
Abraham, Dulcy M. and Leonhard E. Berhold, "Control For Computer-Integrated Construction," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Computerized Applications, Construction
Ibbs, C. William Jr., "Proceedings of a Workshop for the Development of New Research Directions in Computerized Applications to Construction Engineering and Management Studies," University of Illinois at Urbana Champaign, July 1985

Computerized, Leveling
Pellinen, Terhi, "Computerized Leveling Course Design Method," presented at 72nd Annual Meeting of Transportation Research Board, Washington, D.C., January 1993

Concrete Reinforcement

Bernold, Leonhard E. and Md. Salim, "Placement-Oriented Design and Delivery of Concrete Reinforcement," Submitted to the ASCE Journal of Construction Engineering and Management, Special Issue on Computers in Construction, July 1992

Concrete Structures
Tiemeng, By Wang and Qin Quan, "An Expert System for Diagnosing and Repairing Cracks in Cast-in-Place Concrete Structures," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Concrete
Williams, Trefor P., et. al., "A Knowledge-Based Expert System for Quality Assurance of Concrete," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Concrete, Masonry, Steel Construciton Automation
Brown, Steven J. and Major Thomas J. Kelly, "The Effect of Concrete, Masonry, and Steel Construction Automation on Traditional USACE Quality Assurance," USACERL Technical Report, November 1992

Concrete, Pavements
Wells, Gordon K., Hannon, Joseph B. and Predoehl, Nelson H., "California Experience with Cracking and Seating of Concrete Pavements," In Proceedings of the Transportation Research Board, Number 910519, 1991

Construction
Chang, David Y. and E. Lynn Cook, "Construction Coordination: A Knowledge-Based Approach," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Construction
Chang, David, "An Object-Oriented Simulation System for Construction Process Planning," Preparing For Construction In The 21st Century, Proceedings Of Construction Congress '91, ASCE, Cambridge, MA, April 13-16, 1991

Construction Cranes
Shapiro, Lawrence K. and Howard I. Shapiro, "Construction Cranes," undated

Construction
Kim, Moonja Park and Kimberly Adams, "An Expert System For Construction Contract Claims," Microcomputer Knowledge-Based Expert Systems In Civil Engineering: Proceedings Of A Symposium Sponsored By The Structural Division of the American Society of Civil Engineers, Nashville, TN, May 10-11, 1988

Construction
McCahill, Dennis F. and Leonhard E. Bernold, "Simulation for Construction Planning and Control," Excellance In The Construction Project: Proceedings Of Construction Congress I, ASCE, San Francisco, CA, March 5-8, 1989

Construction
Miresco, Edmond T., "Knowledge Based Expert System for Construction Scheduling," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Construction
Muspratt, Murray, "Hi-Tech for Construction Projects," Computers in Industry, 10 (1988) pp. 197-208

Construction
Waugh, Lloyd M., "Knowledge-Based Construction Scheduling," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Construction, Automation
Needs Assessment for Construction Automation, The Construction Industry Institute, July 1991

Construction, Automation, Computer Integrated
Gatton, Thomas Michael, "Designing for Construction Automation: Advanced Automation Technologies for Computer Integrated Construction," Thesis, University of Illinois at Urbana-Champaign, 1991

Construction, Automation, Robotics
Bernold, Leonhard E., "Construction Automation and Robotics Laboratory," North Carolina State U., Raleigh, NC, March 1992

Construction, Automation, Robotics
Nease, A.D., "Air Force Construction Automation/Robotics," Air Force Civil Engineering Support Agency, Tyndall AFB, FL, 1992

Construction, Concrete, Structures
Fischer, Martin, "A Construction Expert System For The Preliminary Design Of Reinforced Concrete Structures," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Construction, Productivity and Cost Evaluation
Chalabi, A. Fattah, "Two Microcomputer Programs For Heavy Construction Equipment Productivity And Cost Evaluation," Computing in Civil Engineering: Microcomputers to Supercomputers, Proceedings of the Fifth Conference, Alexandria, VA, American Society of Civil Engineers, March 29-31, 1988

Construction, Robot
Russell, Jeffery, et. al., "Framework for Construction Robot Fleet Management System," Journal of Construction Engineering and Management, Vol. 116, No. 3, Sept. 1990, pp. 448-463

Construction, Robotics
Singh, Amarjit, "Construction And Robotics: Problems And Solutions," Preparing For Construction In The 21st Century, Proceedings Of Construction Congress '91, ASCE, Cambridge, MA, April 13-16, 1991

Construction, Robots
Russell, Jeffrey S., et. al., "Generic Framework For Evaluation Of Multiple Construction Robots," Preparing For Construction In The 21st Century, Proceedings Of Construction Congress '91, ASCE, Cambridge, MA, April 13-16, 1991

Construction, Schedule, Generation, AI Tools
Echeverry,D., et. al., "Construction Schedule Generation Using AI Tools," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Construction, Scheduling
De La Garza, Jesus, et. al., "Knowledge Elicitation Techniques For Construction Scheduling," Microcomputer Knowledge-Based Expert Systems In Civil Engineering: Proceedings Of A Symposium Sponsored By The Structural Division of the American Society of Civil Engineers, Nashville, TN, May 10-11, 1988

Contractor
Russell, Jeffery S. and Miroslaw J. Skibniewski, "An Expert System for Contractor Prequalification," Computing in Civil Engineering: Microcomputers to Supercomputers, Proceedings of the Fifth Conference, Alexandria, VA, American Society of Civil Engineers, March 29-31, 1988

Control, Robotic, Rebar, Bending
Dunston, Phillip S. and Leonhard E. Bernold, "Adaptive Control for Robotic Rebar Bending," Submitted to the Journal Microcomputers in Civil Engineering, September 1992

Cost Forecasting
Reynolds, Michael F. and George Stukhart, "Project Cost Forecasting," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

CRANE, Optimal Tower Crane
Chalabi, A. Fattah and Christopher Yandow, "CRANE, An Expert System For Optimal Tower Crane Selection And Placement," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

CRANIUM, Sensory, Construction, Equipment, Operators
Everett, John G., "The CRANIUM: A Case Study Of Sensory Improvement for Construction Equipment Operators," Preparing For Construction In The 21st Century, Proceedings Of Construction Congress '91, ASCE, Cambridge, MA, April 13-16, 1991

Damage Assessment," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Database
Chang, Edmund Chin-Ping, "Intelligent Database Applications On Signal Maintenance Activities," Computing in Civil Engineering: Microcomputers to Supercomputers, Proceedings of the Fifth Conference, Alexandria, VA, American Society of Civil Engineers, March 29-31, 1988

Database, Asphalt, Paving
Williams, Trefor P., "A Hypertext Database for Asphalt Paving," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Database, CAD/KBES Integration, Construction
Morad, Ayman A., "A Database Approach for CAD/KBES Integration for Construction Planning," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Database, Concrete
Joss, Craig J., et. al., "A Data Base Program for Preparing and Reporting Concrete Mix Designs," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Database, Highway, Bridges
Puri, Satinder P.S., "A Relational Database For Long-Span Highway Bridges," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Database, Pavement
Schwartz, C.W., et. al., "Database Organization For Airfield Pavement Management," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Database, Seismic, Evaluation, Bridge
Fenves, Gregory L., et. al., "Database Design For Seismic Evaluation Of The San Francisco Bay Bridge," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Database, Tunnel, Estimating
Touran, Ali and Julio Martinez, "A Database For Tunnel Planning And Estimating," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Databases, Automated, Construction
Singh, Amarjit and Miroslaw J. Skibniewski, "Integrating Data Bases For Executing Automated Construction Tasks," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Design, Systems
Franklin, W.R., "Design Systems with Common Sense," Proceedings of the Third Eurographics Workshop on Intelligent CAD Systems: Practical Experience and Evaluation, April 3-7, 1989, Texel, the Netherlands, Springer-Verlag, editors PJW ten Hagen and P. Weerkamp, with Varol Akman and P. Veerkamp

Diagnostic Maintenance, Hydraulic, Miner
Mitchell, Julie, "Diagnostic Maintenance Expert System for the Hydraulic Sub-System of a Continuous Miner," U.S. Bureau of Mines

Digital Elevation Models
Lee, Jay, Snyder, Peter K., Fisher, Peter F., "Modeling the Effect of Data Errors on Feature Extraction from Digital Elevation Models," Photogrammetric Engineering & Remote Sensing, Vol. 58, No. 10, October 1992, pp. 1461-1467

Distress, Pavement, Performance
Distress Identification Manual for the Long-Term Pavement Performance Studies, Strategic Highway Research Program, National Research Council, Washington, DC, 1990

Dump Truck
Sugiura, H., et al., "Autonomous Dump Truck System for Transporting and Positioning Heavy Loads," Proceedings of 10th International Symposium on Automation and Robotics in Construction, Houston, May 1993

Earthmoving Scrapers
Lux, William J., "The Past, Present & Future Of Earthmoving Scrapers," Earthmoving And Heavy Equipment: Proceedings Of The Conference Sponsored By The Committee On Construction Equipment And Techniques, ASCE, Tempe, AZ, February 5-7, 1986

Earthmoving Scrapers
Sotoodeh-Khoo, Hooman and Boyd C. Paulson, Jr., "Sensors And Expert Systems In Production Optimization Of Earthmoving Scrapers," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Earthwork/Resource Estimation
Ward, Carter, "Earthwork And Resource Estimation On Large Expedient Projects," Earthmoving And Heavy Equipment: Proceedings Of The Conference Sponsored By The Committee On Construction Equipment And Techniques, ASCE, Tempe, AZ, February 5-7, 1986

Electrical Diagnostic System, Mining
Berzonsky, Bruce E., "A Knowledge-Based Electrical Diagnostic System for Mining Machine Maintenance," IEEE Transactions on Industry Applications, Vol. 26, No. 2, March/April 1990

Electronic Communication
Meyer, H.W. Guy and Jeffrey Russell, "Electronic Communication Between Project Participants," Preparing For Construction In The 21st Century, Proceedings Of Construction Congress '91, ASCE, Cambridge, MA, April 13-16, 1991

Engineering, Contractor
Russell, Jeffrey S. and Miroslaw J. Skibniewski, "Knowledge Engineering In A Knowledge-Based System For Contractor Prequalification," Microcomputer Knowledge-Based Expert Systems In Civil Engineering: Proceedings Of A Symposium Sponsored By The Structural Division of the American Society of Civil Engineers, Nashville, TN, May 10-11, 1988

Equipment, Pavement

Hudson, W.R., Uddin, G.E. and Reilly, K.T., "Improved Methods and Equipment to Conduct Pavement Distress Surveys," Technical Report FHWA-TS-87-213, FHWA, U.S. Department of Transportation, 1987

Excavating, Casting
CASTEC: Vertical Excavating And Casting, Brochure, Eagle-Pitcher, 1992

Excavation, Underground Technology, Review, Comparison
Dendrou, Basile, "The Excavation and Underground Technology in Europe and the U.S.A.: A Critical Review and Comparison," National Science Foundation, Dec. 1991

Fatigue Evaluation
Chen, Stuart S. and John L. Wilson, "Knowledge Representation for Fatigue Evaluation," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Field, Material, Robot
Field Material Handling Robot (FMR), Data Sheets, Martin Marietta Baltimore Aerospace Co., 1992

Field, Robotic, Pavement
Haas, Carl, et. al., "A Field Prototype of a Robotic Pavement Crack Sealing System," The 9th International Symposium on Automation and Robotics in Construction, Tokyo, Japan, June 3-5, 1992

FMS Approach, Construction, Automation
Bernold, Leonhard E., et. al., "FMS Approach To Construction Automation," Journal of Aerospace Engineering, Vol. 3, No. 2, April, 1990, pp. 108-121

Framework, Applications, Pavement, Management
Grivas, Dimitri A., Reed, N.E., "A Framework for Knowledge Based Applications in Pavement Management," In Workshop on Knowledge Based Expert Systems in Transportation, 1990

Framework, Construction
Abraham, Dulcy M. and Leonhard E. Bernold, "A State-Based Framework For Construction Control," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Future, Construciton, Skills, Joystick
Future Construction Skills To Require Joystick Finesse, ENR, June 15, 1989, p. 11

Fuzzy Petri, Robotic
Cao, T. and Sanderson, A. C., "A Fuzzy Petri Net Approach to Reasoning about Uncertainty in Robotic Systems," submitted to 1993 IEEE International Conference on Robotics and Automation

Fuzzy Petri Nets
Cao, T. and Sanderson, A. C., "Task Sequence Planning Using Fuzzy Petri Nets," IEEE International Conference on Systems, Man, and Cybernetics, 1991

Fuzzy Set Approach, Linguistic Seismic Load/Damage

Souflis, Costas and Grivas, Dimitri A., "Fuzzy Set Approach to Linguistic Seismic Load and Damage Assessments," Journal of Engineering Mechanics, 112(6):605-618, 1986

Gaussian Modelling, Morphological Size Distributions
Bhagvati, Chakravarthy, Skolnick, Michael M. and Grivas, Dimitri, "Gaussian Modelling of Morphological Size Distributions to Increase Sensitivity in Detecting Defects in Textures," CUPR, 1993

Geographic, Highway
Martin, Michael R. et. al., "Using Geographic Information Systems For Highway Maintenance," 4th International Conference on Microcomputers in Transportation, Baltimore, MD, July 22-24, 1992

Geographic, Information
Geographic Information Systems, Brochure, Patton Harris Rust Associates, 1992

Geometric
Krishnan, S. S. and Sanderson, A. C., "Reasoning About Geometric Constraints for Assembly Sequence Planning," Proceedings of 1991 IEEE International Conference on Robotics and Automation

Geometric, Operations, Databases
Franklin, W.R., "Efficient Primitive Geometric Operations on Large Databases," Proceedings National Conference Challenge for the 1990s GIS Geographic Information Systems, Canadian Institute of Surveying and Mapping, Ottawa, Feb. 27 - March 3, 1989, pp. 1247-1256, with Mohan Kankanhalli and Chandrasekhar Narayanaswami

Graph Representation, Assembly Plans
Homem de Mello, L. S. and Sanderson, A. C., "AND/OR Graph Representation of Assembly Plans," IEEE Transactions on Robotics and Automation, vol. 6, no. 2, pp. 188-199, April 1990

Graphical Interface, Bridges
Tenende, Lennard M. and C.P. Johnson, "A Graphical Interface For Curved Steel Girder Bridges," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Ground Vehicles
Lovece, Joseph A., ed., "Unmanned Ground Vehicles," Military Robotics Sourcebook: 1991-1992 Edition, L&B Ltd., Washington, DC
(Including Descriptions of: Attachable Robotic Convoy Capability, p.10; Autonomous Rapid Runway Repair, p. 12; Convoy Speed Control System, p.17; Field Material Handling Robot, p.20; Haz-Trak, p. 28; Pele Remote Control System, p. 57; Remotely Controlled Mobile Excavator, p. 62; Remotely Operated Bobcat, p.63; Robotics for Airbase Recovery Program, p. 79; Telerobotic Excavator, p.99)

Haulage Systems, Miner
Bhatt, S.K., "Continuous Haulage Systems for Computer-Assisted Continuous Miner," Mining Engineering, Oct. 1990, pp. 1184-1189

Haz-Trak
Haz-Trak: Force Feedback Excavator and Material Handling System, Kraft Telerobotics, Overland Park, Kansas, 1992

Hierarchical Real-Time, Coal Mining
Huang, Hui-Min, et. al., "A Reference Model, Design Approach, and Development Illustration Toward Hierarchical Real-Time System Control for Coal Mining Operations," Advances in Control & Dynamic Systems, Academic Press

Hierarchical Real-Time, Coal Mining, Automation
Huang, Hui-Min, "Hierarchical Real-Time Control Task Decomposition for a Coal Mining Automation Project," NIST, March 24, 1990

Hierarchical, Space Truss Assembly
Mathur, R. K., and Sanderson, A. C., "A Hierarchical Planner for Space Truss Assembly," Proceedings of 1990 SPIE Symposium on Advances in Intelligent Systems"

High-Tech Products, Bureau of Mines
Chironis, Nicholas P., "High-Tech Products On The Way From The Bureau Of Mines," Coal, March 1988

Highway Maintenance
Advanced Highway Maintenance Technology Program, (Data Sheets, including: Delineation and Signing Technology; Hazmat Debris and Litter Removal; Landscape Management; Workzone Safety; Pavement Integrity; Structures Maintenance; Maintenance Minded Infrastructure; Paint Striping Guidance System; Paint Striping Information System; Maintenance of the Future; Remote Hazmat Lab;

Highway, Construction, Engineering
Research and Development Program for Highway Construction Engineering Management, Transportation Research Board, National Research Council, Washington, DC, 1991
Highway, Pavement, Surface, Video Image Processing Curphrey, Donald R., Fronek, D.K. and Wilson, James H., "Highway Pavement Surface Remote Sensing Using Video Image Processing," In Proceedings of American Society of Civil Engineers, National Spring Convention, 1985

Highway, Pavement, Surfaces, Reconstruction, Moire Interferometry
Guralnik, Sidney, et. al, "Highway Pavement Surfaces Reconstruction by Moire Interferometry," Applications of Advanced Technologies in Transportation Engineering, Proceedings of the Second International Conference, American Society of Civil Engineers, New York, 1991

Highway, Research
Kruse, Thomas R., Sinha, Kumares C., "Joint Highway Research Project - Final Report," FHWA/IN/JHRP-92/13, The Use of Advanced Technologies in Indiana Department of Transportation

Highway, Stereoscopic, Imaging
Lee, Hosin, et. al., "Measuring Highway Inventory Features Using Stereoscopic Imaging System," Applications of Advanced Technologies in Transportation Engineering, Proceedings of the Second International Conference, American Society of Civil Engineers, New York, 1991

Horizon Signal, Literature, Wayne, PA 1990

Hydraulic, Miner

Mitchell, Julie, "A Knowledge-Based System for Hydraulic Maintenance of a Continuous Miner," 21st Application of Computers and Operations Research in the Mineral Industry, Alfred Weiss, ed., 1989

Hydraulic, Mining Machine, Diagnostic Expert
Mitchell, J., "Hydraulic Maintenance of a Continuous Mining Machine Using Diagnostic Expert System Techniques," SME Annual Meeting, Salt Lake City, UT, 26 Feb.- 1 March 1990

Image Analysis, Micromechanics
Jeulin, D., "On Image Analysis and Micromechanics," Revue Physics Applications, 62:549-556, 1988

Image
Osmont, Phillippe, Jeulin, Dominique, Larquetoux, Gilles, "Simulation of Crack Propagation in a Porous Material By Image Analysis," Acta Sterologica, 6(3):381-386, 1987

Imaging, Pavement
Ritchie, Stephen G., "Digital Imaging Concepts And Applications In Pavement Management," Journal of Transportation Engineering, Vol. 116, No. 3, May/June 1990, pp. 287-298

Injuries, Construction
Bernold, Leonhard E. and Nil Guler, "Analysis Of Back Injuries In Construction," Submitted To the ASCE Journal of Construction Engineering and Management, October 1992

Integrated Design, Construction
Yamazaki, Yusuke, "Integrated Design and Construction Planning by Knowledge-based Systems," Preparing For Construction In The 21st Century, Proceedings Of Construction Congress '91, ASCE, Cambridge, MA, April 13-16, 1991

Integrating Building Design, Construction Scheduling, Cost Estimating
Yau, N.J., et. al., "An Environment For Integrating Building Design, Construction Scheduling, And Cost Estimating," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Investigation, Bridge, Vehicle, Superstructure, Computer, Methodology
Fenske, T.E. and J.Z. Yang, "Investigation Of The Bridge Vehicle/Superstructure Interaction Problem Via Computer-Based Methodology," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

JTEC Panel Report, Construction
Tucker, R.L., et. al., "JTEC Panel Report on Construction Technologies in Japan," Loyola College in Maryland, Baltimore, June 1991

Kinematics/Trajectory Planning, Robotic, Excavation
Vaha, P.K., et. al, "Kinematics and Trajectory Planning for Robotic Excavation," Preparing For Construction In The 21st Century, Proceedings Of Construction Congress '91, ASCE, Cambridge, MA, April 13-16, 1991

KYBAS, Design, Analysis, Highway, Bridges
Fenske, T.E., et. al., "KYBAS: An Expert System For Design And Analysis Of Highway Bridges," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Laod, Highway, Bridge
Fu, Gongkang and Tang, Jianguo, "A Proof Laod Formula for Highway Bridge Rating," In Proceedings of the Transportation Research Board, Number 920465, 1990

Laser Tracking, Mining
Anderson, Donna, "Laser Tracking and Tram Control of a Continuous Mining Machine," U.S. Bureau of Mines, RI 9319, 1990

Laser, Road Surface
Novak, R., "Swedish Laser Road Surface Tester," Proceedings of Roadway Evaluation Equipment Workshop, Technical Report TS-85-210, FHWA, May 1985

Lasers, Electromagnetic
Beliveau, Yvan J., "Automated Position And Control Systems Using Lasers And Electromagnetic Signals," Excellance In The Construction Project: Proceedings Of Construction Congress I, ASCE, San Francisco, CA, March 5-8, 1989

Learning, Innovating, Construction
Bernold, Leonhard E., "Learning and Innovating in a Construction Technology Laboratory," Preparing For Construction In The 21st Century, Proceedings Of Construction Congress '91, ASCE, Cambridge, MA, April 13-16, 1991

Lunar Excavation
Bernold, Leonhard E., "Experimental Studies On Mechanics Of Lunar Excavation," Journal of Aerospace Engineering, Vol. 4, No. 1, Jan. 1991, pp. 9-22

Measurement, Automation, Construction, Assembly
Measurement Technology for Automation in Construction and Large Scale Assembly, National Bureau of Standards, Feb. 1985

Mechanical Assembly
Homem de Mello, L. S. and Sanderson, A. C., "Representations of Mechanical Assembly Sequences," IEEE Transactions on Robotics and Automation, vol. 7, no. 2, pp. 211-227, April 1991

Mechanical Linear Transducers, Mining
Jobes, Christopher, "Utilizing Mechanical Linear Transducers for the Determination of a Mining Machine's Position and Heading," U.S. Bureau of Mines, IC 9254, 1990

Mechanical Sensor, Mining Machine
Jobes, Christopher C., "Mechanical Sensor guidance of a Mining Machine," Tenth WVU International Mining Electrotechnology Conference, West Virginia University, July 24-27 1990

Methodologies, Highwall Miners
Kwitowski, August J. et. al., "Advanced Control Methodologies for Highwall Miners," American Mining Congress Coal Convention, Cincinnati, May6-10, 1990

Microcomputer, Mining
Schiffbauer, William H., "A Microcomputer Network for Autonomous Mining Research," 21st Application of Computers and Operations Research in the Mineral Industry, Alfred Weiss, ed., 1989

Mining Machine
Sammaro, John J., "Heading Control for a Continuous Mining Machine," Mining Automation, 4th Canadian Symposium, Saskatoon, Canada, 16-18 Sept. 1990

Mining Machine
Schiffbauer, William, "A Testbed for Autonomous Mining Machine Experiments," IC 9198, U.S. Bureau of Mines, 1988

Mining Machine, Inertial Sensors, Gravitational Sensors, Magnetic Senors
Sammarco, John, "Mining Machine Orientation Control Based On Inertial, Gravitational, and Magnetic Sensors," U.S. Bureau of Mines, RI 9326, 1990

Mining Machines
Schnakenberg, George H., "Bureau of Mines Research to Automate Continuous Mining Machines," Mining Engineering, Dec. 1990, pp. 1329-1333

Mining, Real-Time Control
Albus, James, et. al., "Mining Automation Real-Time Control System Architecture Standard Reference Model (MASREM): Coal Mine Automation," NIST Technical Note 1261, Volume 1, 1989

Mobile Robot, Branch Wire
Aoshima, Shin-ichi, Tsujimura, Takeshi, "A Multiunit Wire-Mobile Robot that Avoids Obstacles and Transfers to Branch Wires," JSME International Journal, Series III, Vol. 35, No. 1, 1992

Model-based, Estimation, Algorithm
Ravichandran, B. and A. C. Sanderson, "Model-based Pose Estimation using Minimal Representation Criterion and Genetic Algorithm," 1992 SPIE Symposium, November 1992

Modeling, Construction
Rasdorf, William J., et. al., "A Formal Approach to Modeling Construction Data," Computing in Civil Engineering And Symposium On Data Bases, Proceedings of the Seventh Conference, Washington, DC, American Society of Civil Engineers, May 6-8, 1991

Modeling, Construction
Touran, Ali, "Expert System/Simulation Integration For Modeling Construction Operations," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Modelling, Controlling, Road, Finishing
Gourdon, J.L. and Peyret, F., "Modelling and Controlling the Road Finishing Process," Proceedings of 8th International Symposium on Automation and Robotics in Construction, Stuttgart, Germany, June 1991

Morphological Analysis, Pavement, Surface

Bhagvati, Chakravarthy, Grivas, D.A. and Skolnick, M.M., "Morphological Analysis of Pavement Surface Conditions," In E.M. Dougherty, editor, Mathematical Morphology in Image Processing. Marcel Dekker, Inc., New York, 1992

Morphological, Algorithms, Analysis, Pavement, Structure
Grivas, Dimitri A. and Skolnick, Michael M., "Morphological Algorithms for the Analysis of Pavement Structure," In Visual Communications and Image Processing IV, Volume 1199, SPIE - The International Society of Optical Engineering, 1989

Multipurpose Vehicle, Integrated Surface Patcher
Point, G., "Two Major Innovations in Current Maintenance: The Multipurpose Vehicle and the Integrated Surface Patcher," Presented at the 67th Annual Meeting of Transportation Research Board, Washington, D.C., January 1988

PASCO, Road, PRS-System
PASCO Corporation, "1 for 3, PASCO Road Survey System (PRS-System) - From Theory to Implementation," PASCO Corporation, c/o MITSUBISHI International Corporation, Project and Development Div., New York

Pavedex PAS 1, Automated
Lee, Hosin, "Accuracy, Precision, Repeatability and Compatibility of Pavedex PAS 1 Automated Distress Measuring Device," In Proceedings of the Transportation Research Board, Number 910379, 1991

Pavedex, Computer, Pavement, Image
Lee, Hosin, "Evalution of Pavedex Computer Pavement Image Processing System in Washington," In Automated Pavement Distress Data Collection Seminar, 1990

Pavement
Haas, Carl and Hendrickson, C. "Intgegration of Diverse Technologies for Pavement Sensing," Transportation Research Board 70th Annual Meeting, Washington, DC, January 13-17, 1991

Pavement
Hudson, R., Elkins, G., Uddin, W., and Reilley, K., "Improved Methods and Equipment to Conduct Pavement Distress Surveys," Technical Report TS-87-213, FHWA, April 1987

Pavement
Koutsopoulos, Haris N., et. al, "Automated Analysis Of Pavement Distress Data," Applications of Advanced Technologies in Transportation Engineering, Proceedings of the Second International Conference, American Society of Civil Engineers, New York, 1991

Pavement
Mohsen, Jafar P. and Timothy R. Crowder, "Pavement Design Using An Expert System," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Pavement
Ritchie, Stephen G., et. al., "Development of an Expert System for Pavement Rehabilitation Decision Making," Transportation Research Record 1070, pp. 96-103

Pavement, Equipment
Coomasasary, C., "Pavement Markings Equipment," Ministry of Transportation of Ontario, Canada, June 1991

Pavement, Equipment
PASCO USA, Inc., Report on Pavement Condition Monitoring Methods and Equipment, Lincoln Park, NJ, September 1985

Pavement, Equipment, GERPHO
MAP, Inc., Pavement Condition Monitoring Methods and Equipment Final Report on GERPHO, Washington, D.C., August 1986

Pavement, Fractals, Image
LeBlanc, Jeffery, et. al., "Analysis and Generation of Pavement Distress Images Using Fractals," Transportation Research Board 70th Annual Meeting, Washington, DC, January 13-17, 1991

Pavement, Image Analysis
Li, Lan, et. al., "Flexible Pavement Distress Evaluation Using Image Analysis," Applications of Advanced Technologies in Transportation Engineering, Proceedings of the Second International Conference, American Society of Civil Engineers, New York, 1991

Pavement, Image Processing, Neural Networks
Kaseko, Mohamed S. and Stephen G. Ritchie, "Pavement Image Processing Using Neural Networks," Applications of Advanced Technologies in Transportation Engineering, Proceedings of the Second International Conference, American Society of Civil Engineers, New York, 1991

Pavement, Images
Dunston, Phillip S. and Leonhard E. Bernold, "Adaptive Control for Robotic Rebar Bending," Submitted to the Journal Microcomputers in Civil Engineering, September 1992

Pavement, Pavements, Maintenance
Schoemberger, Gerhard, "A Pavement Management Information System for Evaluating Pavements and Setting Priorities for Maintenance," Transportation Research Record 951, pp. 60-63, 1984

Pavement, Photography
Hintz, Raymond J., Karakadas, Christos and Kang, Joon-Mook, "Analysis of Pavement Cracking and Rutting Using Close-Range Photography," Photogrammetric Engineering and Remote Sensing,

Pavement, Radar, Bore Hole Camera
Inagaki, M., "Subsurface Pavement Structure Inventory Using Ground Penetrating Radar and a Bore Hole Camera," Applications of Advanced Technologies in Transportation Engineering, Proceedings of the Second International Conference, American Society of Civil Engineers, New York, 1991

Pavement, Video Images
Butler, Bertell C., "The Pavement Distress Imager Quantifying Pavement Cracking From Video Images," Transportation Research Board 70th Annual Meeting, Washington, DC, January 13-17, 1991

Pavement, Video, Image
Longnecker, Keith E., "Pavement Surface Video Image Work in Idaho," In Automated Pavement Distress Data Recognition Seminar, Ames, Iowa, June 1990

Pavements
Aougab, Hamid, et. al., "Expert System for Management of Low Volume Flexible Pavements," Computing in Civil Engineering: Microcomputers to Supercomputers, Proceedings of the Fifth Conference, Alexandria, VA, American Society of Civil Engineers, March 29-31, 1988

Petri Nets
Cao, T. and Sanderson, A. C., "Task Decomposition and Analysis of Assembly Sequence Plans Using Petri Nets," Proceedings of the Third International Conference on Computer Integrated Manufacturing, Rensselaer Polytechnic Institute, 1992

Potholes
Artificial Intelligence to Aid in War on Potholes, ENR, December 12, 1985, p.31

Ray, Malcolm H. and David Logie, "An Object-Oriented Approach To Warranting Roadside Safety Hardware," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Real-Time
Oberlender, Garold D., "Real-Time Project Tracking," Excellance In The Construction Project: Proceedings Of Construction Congress I, ASCE, San Francisco, CA, March 5-8, 1989

Real-Time, Construction
Paulson, Boyd C. Jr. and Hooman Sotoodeh-Khoo, "Teaching Experiment In Real-Time Construction Data Acquisition," Earthmoving And Heavy Equipment: Proceedings Of The Conference Sponsored By The Committee On Construction Equipment And Techniques, ASCE, Tempe, AZ, February 5-7, 1986

Research, Construction, Automation
Bernold, Leonhard E., "Laboratory And Field Research in Construction Automation," Preparing For Construction In The 21st Century, Proceedings Of Construction Congress '91, ASCE, Cambridge, MA, April 13-16, 1991

Remote Control
Parsons, H. McIlvaine, "Teleoperator Interfaces for Remote Control Centers/Test Beds," Proceedings of the Human Factors Society 33rd Annual Meeting - 1989

Remote Controlled Excavation
Wohlford, William, et. al., "New Capability for Remote Controlled Excavation," SAE International Off-Highway & Powerplant Congress and Exposition, Milwaukee, WI, Sept. 11-14, 1989

Remotely Operated Unmanned Land Vehicle
Szabo, Sandor, et. al., "Control System Architecture for a Remotely Operated Unmanned Land Vehicle," Proceedings of the 5th International Symposium on Intelligent Control, Philadelphia, PA, Sept. 1990

Retaining Wall
Adams, Teresa M., Barrett, Robert K. and Wang, Trever, "Colorado's Knowledge System for Overview of Retaining Wall Selection", presented at 72nd Annual Meeting of Transportation Research Board, Washington, D.C., January 1993

Road
The Roads Ahead, Civil Engineering, April 1992, pp. 55-57

Road, Pavement
Williams, Jr., Howard M., "Detection of Cracks in Road Pavement," MS Thesis, Troy, NY 12180, 1986

Roads
Connecticut Tries Movable Barrier, Better Roads, June 1990

Roadside Safety

Roadway Equipment
Dewilder, M., "GERPHO and the APL.," Proceedings of Roadway Evaluation Equipment Workshop, Report TS-85-210, FHWA, May 1985

Robot
Albus, James and Ken Goodwin, "The NIST Spider: A Robot Crane," National Institute of Standards and Technology, Gaithersburg, MD, 1992

Robot
Murphy, S.H. and Wen, J., "Force Decomposition in Robot Force Control," in Proceedings of the 1991 American Control Conference, pp. 2533-2538, June 1991

Robot
Rahimi, Mansour and Karwowski, Waldemar, "Human-Robot Interaction," Remote Control Units, H.M. Parsons

Robot
Seward, Derek, "Lucie - The Autonomous Robot Excavator," Industrial Robot, Vol. 19, No. 1, 1992, pp. 14-18

Robot
Wang, Mao-Jiun, et. al., "A Decision Support System for Robot Selection," Decision Support Systems 7 (1991), pp. 273-283

Robot
Warszawski, A. and R. Navon, "Robot for Interior-Finishing Works," Journal of Construction Engineering and Management, Vol. 117, No. 3, Sept. 1991, pp. 402-423

Robot, Asphalt
Umeda, R. et al., "Development of a Robot Asphalt Paver," Proceedings of 10th International Symposium on Automation and Robotics in Construction, Houston, May 1993

Robot, Field Applications
Johnson, Daniel W., et. al., "Towards an Autonomous Heavy Lift Robot for Field Applications," Martin Marietta Aero & Naval Systems, Baltimore, MD, 1990

Robotic Backhoe
Huang, Xiaodong and Bernold, Leonhard E., "Adaptive Control for Robotic Backhoe Excavation," presented at 72nd Annual Meeting of Transportation Research Board, Washington, DC, January 1993

Robotic Excavation
Bernold, Leonhard E., "Motion And Path Control For Robotic Excavation," Submitted to the ASCE Journal of Aerospace Engineering, September 1990

Robotic Manipulator Platform
Huang, Xiaodong and Bernold, Leonhard E., "Configuration and Components of the Multipurpose Robotic Manipulator Platform (MRMP)," Appendix to Technical Report CARL-92-02, North Carolina State U., Raleigh, NC, September 1992

Robotic Manipulators, Mobile Platform
Murphy, S.H., Wen, J., and Saridis, G., "Simulation of Cooperating Robotic Manipulators on a Mobile Platform," IEEE Transactions on Robotics and Automation, vol. 7, pp. 468-478, August 1991

Robotic
Normile, Dennis, "Robotic Roundup," Civil Engineering, May 1989, pp. 76-79

Robotic
Sanderson, A. C., "Deployable Robotic Structures," CIRSSE Technical Report, Rensselaer Polytechnic Institute, August 1992.

Robotic
Watson, J.F., Lefebvre, D.R., Desrochers, A.A., Murphy, S.H. and Fieldhouse, K.R., "Testbed for Cooperative Robotic Manipulators," in Intelligent Robotic Systems for Space Exploration, edited by A.A. Desrochers, Kluwer Academic Publishers, Ch. 1, 1992

Robotic, Construction
Robotic Applications To Construction, Cost Engineering, Vol. 31, No. 6, June 1989, pp. 10-17

Robotic, Construction
Wing, Robert, "Robotic Joining Technology for Building Construction," Industrial Robot, Vol. 19, No. 1, 1992, pp. 19-20

Robotic, Fuzzy Petri Nets
Cao, T. and Sanderson, A. C., "Sensor-based Error Recovery for Robotic Task Sequences Using Fuzzy Petri Nets," Proceedings of 1992 IEEE International Conference on Robotics and Automation

Robotic, Manipulator Platform
Huang, Xiaodong and Bernold, Leonhard E., "The Multipurpose Robotic Manipulator Platform," Technical Report CARL-92-02, North Carolina State U., Raleigh, NC, March 1992

Robotic, Mining
Schiffbauer, William H., "Distributed Communications and Control Network for Robotic Mining," NASA Conference on Space Telerobotics, Pasadena, CA, Jan. 31 - Feb. 2, 1989

Robotic, Road
Robotic Road Repair, News Item, undated.

Robotic, Soil Sampler, Hazardous Waste
Jaselskis, E.J. and Anderson, M.S., "Robotic Soil Sampler for Hazardous Waste Clean Up," Proceedings of 9th International Symposium on Automation and Robotics in Construction, Tokyo, Japan, June 1992

Robotics, Automation, Highway
Ravani, B. and T.H. West, "Applications of Robotics and Automation in Highway Maintenance," Applications of Advanced Technologies in Transportation Engineering, Proceedings of the Second International Conference, American Society of Civil Engineers, New York, 1991

Robotics, Construction
Kangari, Roozbeh and Daniel Halpin, "Potential Robotics Utilization in Construction," Journal of Construction Engineering Management, Vol. 115, No. 1, March 1989, pp. 126-143

Robotics, Construction
Kangari, Roozbeh and Tetsuji Yoshida, "Prototype Robotics in Construction Industry," Journal of Construction and Engineering Management, Vol. 115, No. 2, June 1989, pp. 284-301

Robotics, Construction
Robotics In Construction: Proceedings, Carnegie-Mellon University, Pittsburgh, PA, April 1985

Robotics, Construction
Warszawski, Abraham, "Robotics in Building Construction," Carnegie Mellon University, Pittsburgh, PA, May 1984

Robotics, Excavation
Bullock, Darcy M. and Irving J. Oppenheim, "Object-Oriented Programming In Robotics Research For Excavation," Journal of Computing in Civil Engineering, Vol. 6, No. 3, July 1992, pp. 370-385

Robotics, Highway, Construction, Maintenance
Zhou, Tong and Thomas West, "Assessment of the State of the Art of Robotics Applications in Highway Construction and Maintenance," Applications of Advanced Technologies in Transportation Engineering, Proceedings of the Second International Conference, American Society of Civil Engineers, New York, 1991

Robotics, Highway, Construction, Maintenance
Zhou, Tong, "Assessment of the State Of The Art Of Robotics Applications in Highway Construction and Maintenance," California Dept. of Transportation, Sacramento, CA, May 1991

Robotized
Peyret, R. and Deparis, J., "The Robotized Shadow Vehicle," Proceedings of 10th International Symposium on Automation and Robotics in Construction, Houston, May 1993

Robots
Johnstone, Bob, "Robots To The Rescue," Eastern Econmic Review, 31 Dec. 87, pp. 52-53

Robots
Robots Move in to tackle Heavier Weights On Building Sites, New Scientist, 2 Sept. 1989

Robots, Automated Systems, Construction
Bradley, D.A. and Seward, D.W., "Robots and Automated Systems for the Civil and Construction Industries," Department of Engineering, University of Lancaster, Bailrigg, Lancaster LA1 4YR, UK

Robots, Construction
Warszawski, A., "Robots in the Construction Industry," Robotica, Vol. 4, pp. 181-188, 1986

RQS Industries, Inc., Literature, Joplin, MO, 1990

Rule-based System, Hazardous Waste Landfills
Rossman, Lewis A. and James T. Decker, "A Rule-Based System For Evaluating Final Covers For Hazardous Waste Landfills," Expert Systems For Civil Engineers: Knowledge Representation, ACE, New York, 1992

Safety
Smith, K., "Work Zone Safety Devices Slated for State Trials This Year," Strategic Highway Research Program Focus (periodical), April 1991

Scattered RI Method
Takada, T. et al., "Using Scattered RI Method," Proceedings of 9th International Symposium on Automation and Robotics in Construction, Tokyo, Japan, June 1992

Sensor-Based, Robots, Visual
Mathur, R. K. and A. C., and Neuman, C. P., "Dynamic Sensor-Based Control of Robots with Visual Feedback," IEEE Journal of Robotics and Automation, vol. RA-3, no. 5, pp. 404-417, October 1987

Sensor-Integrated, Construction
Miller, Mark L. and Leonhard E. Bernold, "Sensor-Integrated Nailing For Building Construction," Journal of Construction Engineering and Management, Vol. 117, No. 2, June 1991, pp. 213-225

Shape Matching
Joshi, R. and Sanderson, A. C., "Shape Matching from Grasp using a Minimal Representation Size Criterion," submitted to the 1993 IEEE International Conference on Robotics and Automation

Shovel
Langreth, Robert, "Smart Shovel," Popular Science, June 1992, pp. 82+

Site Operations
Pagdadis, Sotiris, "Conceptual Model For A Site Operations Control System," Preparing For Construction In The 21st Century, Proceedings Of Construction Congress '91, ASCE, Cambridge, MA, April 13-16, 1991

Sitework Construction, Automation
Brown, Steven J. and Major Thomas J. Kelly, "The Effect of Sitework Construction Automation on Traditional USACE Quality Assurance," USACERL Technical Report, November 1992

Smart Herbicide Applicator; Litter Bag Retrieval; Telerobotics in CALTRANS Maintenance; Automated Raised Marker Placement; Crack/Joint Sealing Machine), California Dept. of Transportation, Sacramento, CA, 1992

Software, Mining
Ausefski, David B., "Researchers Interface Software for Computer Based Mining System Development and Testing," Tenth WVU International Mining Electrotechnology Conference, West Virginia University, July 24-27 1990

Software, Project Management
Clark, Thomas and A.P. Young, "Implementation of Software for Project Management," Computing in Civil Engineering: Microcomputers to Supercomputers, Proceedings of the Fifth Conference, Alexandria, VA, American Society of Civil Engineers, March 29-31, 1988

Soil-Compaction, Vibratory Rollers
Pietsch, D., "Simulation of Soil-Compaction with Vibratory Rollers," Proceedings of 8th International Symposium on Automation and Robotics in Construction, Stuttgart, Germany, June 1991

Specular Surface, Highlight Images, Gaussian Images
Nayar, S. K., Sanderson, A. C., Weiss, L. E., and Simon, D. A., "Specular Surface Inspection Using structured Highlight and Gaussian Images," IEEE Transactions on Robotics and Automation, vol. 6, no. 2, pp. 208-218, April 1990

Ambrose, Dean, "Using Speech Technology in the Mining Industry," Speech Technology, Oct/Nov 1989, pp. 34-37

Spray Patcher
Rollings, R., Korgemagi, P., and Lynch, D., "An Evalution of a High Production Integral Spray Patcher," December 1985

Stochastic, Propagation, Rupture, Surfaces, Slopes
Grivas, Dimitri A. and Harr, Milton, "Stochastic Propagation of Rupture Surfaces Within Slopes," In Proceedings of International Conference on Application of Statistics and Probability to Soil and Structural Engineering, pages 33 - 53, 1975

Stone Cutting
Bernold, Leonhard E. and Davis B. Reinhart, "Process Planning For Automated Stone Cutting," Journal of Computing in Civil Engineering, Vol. 4, No. 3, July 1990, pp. 255-268

Surface, Pavement
Ritchie, Stephen G., et. al., "Surface Condition Expert System For Pavement Rehabilitation Planning," Journal of Transportation Engineering, Vol. 113, No. 2, March 1987, pp. 155-167

Surveying

Automated Surveying Aids I-280 Retrofit, Civil Engineering, Dec. 1990, pp. 26-27

Task, Analysis, Design, Pavement, Management
Grivas, Dimitri A., "Use of Task Analysis for Knowledge Base Design in Pavement Management," Strasse and Verkehr, 2:109 - 113, 1992

Teleoperated EL200B Excavator
Teleoperated EL200B Excavator, Caterpillar Corp. Data Sheet, 1992

Telerobotics
Harbur, Steve, "Telerobotics: A Technology Worthwhile To Man," Utility Construction & Maintenance, June/July 1992, pp. 18-23

Tools, Damage Assessment
Zhang, X.J., et. al., "Tools For Expert System Development In

Transportation
University of Alaska Fairbanks, Alaskan Transportation Technology Transfer Program - Planning, Design and Field Notes, 1991

Transportation, Construction, CAD, Real-Time Positioning
Beliveau, Yvan J., "Transportation, Construction, CAD, Real-Time Positioning Systems," presented at 72nd Annual Meeting of Transportation Research Board, Washington, D.C., January 1993

TSA Remote Excavator
TSA Remote Excavator (T-Rex), Data Sheets, Martin Marietta Baltimore Aerospace Co., 1992

Tunneling
Touran, Ali and Ahmed Banafa, "Probabilistic Scheduling in Tunneling," Computing in Civil Engineering: Computers in Engineering Practice, Proceedings of the Sixth Conference, Atlanta, GA, American Society of Civil Engineers, Sept. 11-13, 1989

Unmanned Ground Vehicles
Szabo, Sandor, et. al., "Control System Architecture for Unmanned Ground Vehicles," Proceedings of AUVS-90, Dayton, Ohio, 1990

Video Distress
Copp, Robert, "Field Test of Three Video Distress Recognition Systems", In Automated Pavement Distress Data Recognition Seminar, Ames, Iowa, June 1990

Video, Image Processing, Pavement
Acosta, Adolfo J., Figueroa, Ludwig J., Mullen, Robert L., "A Low Cost Video Image Processing System for Evaluating Pavement Surface Distress", Proceedings of the Transportation Research Board, Number 920407, 1992
Virtual Reality/Telepresence
Stone, Robert, "Virtual Reality and Telepresence," UK National Advanced Robotics Research Centre, University Road, Salford M5 4PP (UK), 1991

Visual, Robots
Thorpe, C., "Outdoor Visual Navigation for Autonomous Robots," Proceedings of Intelligent Autonomous Systems II Conference, Amsterdam, December 1989

Voice Recognition Systems
Songer, Anthony D., et. al., "Integrating Voice Recognition Systems with the Collection of Project Control Data," Excellance In The Construction Project: Proceedings Of Construction Congress I, ASCE, San Francisco, CA, March 5-8, 1989

3-D Positioning, Construction, Surveying, Automation
Beliveau, Yvan J., "3-D Positioning for Construction Surveying and Automation," Preparing For Construction In The 21st Century, Proceedings Of Construction Congress '91, ASCE, Cambridge, MA, April 13-16, 1991

3-D Visual, Space-based, Robotic
Page, L., Noseworthy, J. R., Sanderson, A. C. and Gerhardt, L. A., "A 3-D Visual Pose Estimation System for Space-based Robotic Assembly," Proceedings of ASME Winter Annual Mtg., Anaheim, CA, November 1992