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

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U.S. DEPARTMENT OF COMMERCE
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TECHNOLOGY ADMINISTRATION
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NATIONAL INSTITUTE OF STANDARDS
AND TECHNOLOGY
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FINAL REPORT

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To:
FEDERAL HIGHWAY ADMINISTRATION

Prepared by:

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Dr. Ernest Kent

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1ST WORKSHOP REPORT: INDUSTRY VIEWS AND REQUIREMENTS

Automation/Robotics For Road Construction, Maintenance And Operations Workshop

November 4, 1992

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PURPOSE

On November 4, 1992, the first *Workshop on Automation/Robotics for Road Construction, Maintenance, and Operations* was sponsored by the Office of Advanced Research of the Federal Highway Administration (FHWA) and hosted by the Robot Systems Division of the National Institute of Standards and Technology (NIST) at Gaithersburg, Maryland. The purpose of the Workshop was to bring together experts from government, industry, and academia, including construction contractors, equipment manufacturers, federal and state highway officials, and researchers, to discuss the prospective use of automation/robotics in road construction, maintenance, and operations. (A list of attendees can be found in **Appendix A**).

The Workshop was to serve as the initial gathering in a series of year-long events to inaugurate the new FHWA research program in automation and robotics. It was a means to provide the technology developers with a reality check from the users, the highway construction, maintenance, and operations experts. It was an initial mechanism to examine the requirements and opportunities for automation/robotics in highway systems.

The purpose of this report is to document the workshop, including presentations, participant discussions, and the results of working group deliberations. A videotape of the Workshop is available at 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 (pertinent literature, now at NIST, is listed in **Appendix B**). 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

But it is really up to the *users* of the new technology (the highway contractors and departments) to tell the *developers* (the automation experts) what they really want - what will make a crucial difference on the job site. And the automation equipment must be practical - it must do the job better, faster, or cheaper.

A PRECIS OF THE WORKSHOP

The following description of the Workshop paraphrases the various presenters and participants in an attempt to summarize the key issues discussed.

Dr. Ernie Kent

Dr. Ernie Kent, of the Robot Systems Division of NIST, welcomed the representatives of the highway and scientific communities attending the Workshop. The goal of the Workshop, he stated, was to allow the technical community to learn what are the important issues from the perspective of the highway community. The principal work of the day will fall on the highway community.

Dr. Kent introduced Bob Finkelstein, of Robotic Technology Inc., who helped organize the Workshop. All problems and complaints should be directed at Bob, suggested Dr. Kent.

Dr, Kent then introduced the moderator for the Workshop, Dr. Richard Wright, Director of the Building and Fire Research Laboratory at NIST, Dr. Charles Woo, Research Manager For Robotics at the Office of Advanced Research of the FHWA, sponsor of the Workshop, and Mr. Tom Pasko, Director of the Office of Advanced Research of the FHWA.

Dr.Charles Woo

Dr. Woo, in his introductory remarks, noted that automation, in the context of interest, should be all-inclusive, including the entire life-cycle of the highway system. Robotics technology promises to improve safety and increase productivity, and the technology is sufficiently established to warrant serious consideration for use in highway construction, maintenance, and operations.

Robotics can be used in all phases of highway construction: production of highway materials, construction of highways (including quality control), highway maintenance and operations (including inspection and monitoring) - especially in environments which are hazardous or difficult to access.

Thus far, use of this technology in highway transportation has been limited due to a lack of understanding of the technology and a lack of overall research planning for applications of this technology to highway transportation. Therefore, the FHWA is sponsoring a study to be conducted by NIST, an in-depth evaluation of the feasibility of robotics to highway construction, maintenance, and operations. It will include an assessment of the current technology, as well as the development of new highway improvements and methods. The study does not include robotics applications to the Intelligent Vehicle Highway System (IVHS). The DoT IVHS program has its own robotics applications research.

The first step in this study is to hold this one-day Workshop of knowledgeable industry experts, construction contractors, and equipment manufacturers, for a strategic plan of research. We look forward to a frank exchange of opinions and ideas by all participants.

Dr. Richard Wright

The procedure for the Workshop is:

(1) There will be a few words about the objectives and how they were organized.

(2) Dr. Leonhard Bernold will give his view of the state-of-the-art of automation and robotics technology - a view to be used in subsequent discussions to describe how these technical abilities can be directed to support the needs of highway engineering through the whole life cycle (design, construction, operation, maintenance, and repair. The FHWA wants to understand - and we want to understand - from the users how robotics and automation can respond to the needs of the highway community.

(3) We will have a plenary issues-raising session, to look at candidate issues to be explored for the effective application of automation and robotics.

(4) We will separate into working groups, which will use their judgement and information from the plenary session, to point out what they think are the issues and how the issues should be addressed by the FHWA and highway community working together.

(5) The working groups will then report to the plenary session, and everyone will seek to synthesize, out of the five views of the five working groups, some reasonable consensus as to the most important issues to be explored for bringing automation and robotics into effective use in the highway system.

The Workshop is being videotaped, but opinions will not be ascribed to specific individuals in order to encourage participants to be candid.

Goals And Objectives

It is not only the hardware moving things on the work site that is important, but also the information management that takes place throughout the whole highway process.

A previous workshop six years ago at NIST, concerning automation in construction in large scale assemble, was similar in purpose to this one but focused on shipbuilding, building construction, aircraft manufacturing and the like. The technology that emerged as the top priority in that workshop was a site positioning system - a system that would automatically record, in real-time, on the site, what is there and where is it. It came to the top of the list because we need this system whether or not there is a robot on the site. Likewise, a highway engineer would find it valuable to know, any time day or night, what is on the site, what condition it is in, and where it is being stored. The Construction Industry Institute and other organizations are now working to bring this technology to reality.

The objectives of this Workshop (please see **Appendix C**) are to:

* *Define the functional needs that can be met by automation and robotics*, such as obvious needs for safety.

* *Define technological developments required to meet these needs.* Some technology is available off-the-shelf and some is not yet ready. Highway engineering is not a low-tech industry, and it has challenging informational requirements.

* Define organizational and institutional changes needed to exploit automation and robotics for highways. Institutional and organizational problems must be addressed before we can take advantage of the capabilities of automation in the highway enterprise. That is why it is important to have highway system people here to address institutional barriers, which are just as important as the technical barriers, and why we need to start early on overcoming them. We need to be sensitive to these kinds of issues - and to legal issues as well.

In the typical progression of innovation, a process which is relevant to the introduction of new technology to the highway system, there are three major steps:

(1) An existing product or process is replaced with innovation.

(2) A product or process is modified to exploit the potential of innovation.

(3) Roles and responsibilities are modified to fit the new environment.

For example, we can replace the flagman with a robot, where the immediate advantage is that the robot can be hit by a car but leave no widow. This type of substitution is only the first step in innovation because once you get new technology you want to change products or processes to fully exploit the new technology. For example, welding replaced rivets, but the connections still looked as if they were to be riveted or bolted. But after people got comfortable with the new technology, the nature and shapes of the connections were changed to take advantage of the welding process. Another example: automobiles were, at first, really horseless carriages.

Hopefully, in addition to seeing how we can replace existing equipment with robotics and automation, we can get second thoughts about how to change whole procedures and products to take advantage of robotics technologies.

We may not get to it this meeting, but when we introduce new technologies, and modify products and processes to exploit these technologies, we begin to see that organizations, roles, and responsibilities have to change to deal with the technologies. For example, in highway bridge engineering, we have gone beyond the point where an engineer designs the bridge and a contractor builds it. The contractor now introduces a new design and the final product is a result of synthesis. With improved information flow and techniques for the design, construction, operation, and maintenance of highways, we will see changes in the way highway systems are procured and managed. This is a bit beyond our charter for today, but we should keep it in mind because there are important issues here for the FHWA to attend to early in the program.

Dr. Leonhard Bernold

It is impossible to present the state-of-the-art of robotics in the time available. The goal is to share some of the important lessons learned, to present a framework with a global, rather than local, view. We will highlight some of the needs identified, highlight some basic concepts, and provide a common sense approach, mixed with some far-out ideas because it doesn't hurt to dream (please see the Charts in **Appendix D**).

There are many definitions of automation, but it doesn't really matter which one picks. One motivation to automate is safety, but what is the broad issue? Back injury is one of the most crucial, costly safety issues. By far back injuries are greatest percentage of injuries (over 24% - the next highest, finger or knee injuries, are at about 7%), and the cost is horrendous. The average weight of cement bags is 94 pounds, while a man can lift 60-65 pounds on a regular basis. Technology can be used so people do not have to lift, as in Germany where there is a mechanical slave that moves bricks for workers.

Automation, in addition to providing safe and humane workplaces, reducing waste, supporting workers, providing consistently high quality, and increasing productivity, can provide other benefits to mankind, such as aesthetics - beauty and art. Robots can, for example, make stone mosaics more affordable so that can be used more widely.

But automating a mess just leads to an automated mess. Processes and facilities need to be reorganized to accommodate automation, and just the reorganization itself can increase productivity by improving the flow of materials and reducing waste - <u>before</u> any robots are actually introduced. As an example of a mess, just consider a typical construction site where rebars are scattered all over the site.

There are several steps in the life-cycle of data and objects of construction which are amenable to automation: need; concept studies; design/engineering; planning/detailing; procurement; construction; operation; rehabilitation; operation; and demolition. Streamlined material and data flows can be achieved with enhanced electronic and mechanical systems having suitable computer interfaces. For example, rebar bending, which is currently a manual process, can be automated on a conventional rebar bending table with a computer-controlled system using sensory feedback from the bending process and motor control of the bending process. But this system can be expanded to automate process planning, to include information on where and when the bars are needed. We need to look at automating the entire system, not just the bending of the bar.

With computer-aided design and drafting, and automated process planning, we can eliminate some activities and consequent delays in the electronic data flow in tasks preceding construction, operation, and maintenance. At the construction site, where there are robotic excavators and the like, robotic systems should be linked to the data stream to guide the work. Physical systems (robotic excavators and dozers, for example) and processes should be linked together and the data stream: this is the dream.

Large robotic systems, like excavators (which are being developed in Japan), can work accurately and precisely using site measurement and position techniques, such as provided by laser positioning systems. There is immediate feedback from the excavator as to where it is and what it is doing. Such systems can get people out of ditches, which is a very dangerous environment, and increase productivity. NIST, for example, has the SPIDER robotic crane which can be used in road construction.

There are also simple things which can be automated to support the worker, such as a smart nailer. It incorporates a stud sensor to allow the nailer to find the stud and drive the nail into it. It allows an inexperienced worker to perform as if he were a skilled craftsman. Skilled craftsmen do not benefit much from such technology, but less skilled workers improve considerably.

Bar codes are a tremendous technology with lots of opportunities in road construction, including data entry, tracking of materials, and bridge maintenance. Speech recognition and pen-based computing, are useful automation tools for people who don't like to type or write, like some construction foremen.

Prototyping is very important. Get prototypes to the field to serve as catalysts, especially for people who are reluctant to change, and to generate synergy among different individuals and groups.

To achieve competence, commitment, and effectiveness in the introduction of automation and robotics for highway applications, government, industry, and academia must work together, perhaps for 10, 20, or 30 years. Government must provide leadership. In academia, students, excited by the technology, can work with industry performing useful research with practical results based on actual field experience.

In summary:

* Automation should start with cleaning up the mess.

* Automation should be based on a global, rather than a local, view.

* An electronic data trail can serve as a direct thread for thinking globally.

* Multi-disciplined, multi-organizational technology and processes should be emphasized.

* Many inexpensive prototypes and field types should be employed to get the technology rapidly into the hands of the users, to get them excited and energized.

Mr. Thomas Pasko

The Office of Advanced Research (please see **Appendix E**) is interested in making big improvements, with respect to the infrastructure, in productivity and effectiveness. For example, in the late 1950s we switched from the old form riding concrete placement equipment, which had a paving crew of about 100 people. We developed the slip form paver and the paving crew was reduced to about 25 people. Now we would like to reduce the 25 people to 10, if we can do it.

With highways, we have a disaggregated market. There is an incorrect impression that the FHWA owns all the roads and order the use of new technology. It doesn't work that way. FHWA owns 6% of the roads, like the GW Parkway and Dulles Access Road. The FHWA works with the states, which own 23% of the roads. The remaining 71% is owned by 39,000 local units (such as counties, municipalities, and townships). This disaggregated market must be sold on the technology as well - 39,000 units, plus the district offices of the states, plus the regional offices of the FHWA. *It is very difficult to get anything new into practice.* The technology is very traditional and brute-force oriented.

There are about 600,000 people in the various highway departments and FHWA, plus 39,000 organizations as well.

There is a federal aid system which gets funding into 22% of the highways, so 78% have no federal money at all. So FHWA's influence is limited. (But the 22% handle 80% of the traffic - federal aid roads are high-value). FHWA works primarily through a federal aid partnership: federal funding goes to states, which then match the funding. The result is like having 50 countries doing their own thing.

The FHWA encourages research and tries to get people to use it. Often they will use new technology when there are financial incentives, and then revert back to what they are comfortable with when the incentives are gone.

The Office of Advanced Research includes the areas of: national service center; decision analysis in transportation; energy conservation related technology; high performance materials; self-monitoring systems; computer driven technologies; and robots/automation/man-machines. The latter includes the use of robots and automation for production, construction, maintenance, continuous quality control, and hazardous environments.

As an indication of what the states think, consider one recent, important report, from Purdue University, on the use of advanced technologies in the Indiana Department of Transportation. It noted that very few states actually have projects in robotics. It is getting very little emphasis, except in California. Most of the research and development is in computerized design, analysis, and planning; database management and information systems; and highway traffic operations and management. In terms of the actual use of computer technology in State DoTs (as of 1985), there was no robotics or artificial intelligence in use. Database management topped the list of computer use.

There are many possible barriers to the adoption of advanced technology. Key barriers, as determined by survey, are: high initial cost; lack of trained personnel; high operation and maintenance cost; general resistance to change; uncertainty about potential benefits; and uncertainty about the type of technologies that can be used.

As an egregious example of a hazardous job which might be automated, and which was photographed, consider a worker who is sitting on the skids of a hovering helicopter repairing an electrical high-tension wire.

Unmanned, miniature helicopters have been used by the FHWA to inspect bridges (and CALTRANS has a similar project). The military has advanced, high-tech unmanned air vehicles (UAVs) while the FHWA has low-tech ones. A technology gap exists. We must change paradigms and procedures to adopt military systems for highway use.

We can create "pull" for technology. We want to have intergovernmental activities, like with NIST, to create synergies, to use new technology, such as automation and robotics, in areas that the government controls. We can get around building codes and liability issues, and the like, by using new technology in government-owned facilities. The U.S. government owns 230,000 miles of highway, supports 270,000 bridges, owns 417,000 buildings, etc. We can do many experimental projects on government facilities, and many products can be made in government facilities.

Brainstorming Session With Dr. Richard Wright

We would like to generate ideas for consideration in the working groups. As a starting point for discussions, we will first consider *needs* or *requirements* for highway systems performance, followed by the *opportunities* for automation/robotics in highway systems.

Requirements for highway system performance might consist of:

* *Economy* (in terms of life cycle perspective, not just first costs)

* *Functionality* (how well do they really serve the needs of the users of the highway system?)

* *Durability* (do they maintain their initial properties effectively over time?)

* *Time Savings* (time is money, so reduce the times for design, construction, operations, and maintenance)

* *Safety* (most likely to gain substantial attention)

* *Environment* (the system should be environmentally benign)

* *Regulatory Compliance* (look at ways robotics/automation can reduce the burden of dealing with regulations)

What are the requirements from the point of view of state and local governments, FHWA, materials suppliers, contractors, etc.? Which are the most important? Which are easiest to do? Most important to CALTRANS is safety - to get workers off the road.

Opportunities in automation/robotics include:

* Measurement and site data acquisition

* Automation of quality assurance and inspection

* Materials handling and management

* Earth moving, fabrication, placement, finishing

* integrated project information systems

* Project management

* Operations, maintenance, repair

The Workshop will separate into five heterogenous groups. The objectives of the groups will be to determine: on which priorities, with respect to road construction, maintenance, and operation, automation/robotics should focus, and what are the most important issues. Each group will report its findings to the rest of the Workshop.

Before separating into groups, the plenary session will first generate an initial list of the most important **requirements** or needs for the groups to consider:

* Safety

* Durability (which is related to safety - do it carefully and it lasts a long time)

* Simple to regulate (so contractors will use them)

* Performance-based requirements (define system requirements to use automation/robotics as a given; characterize user's <u>needs</u>)

* Open systems

* Able to define clear economic benefits (performance-related specifications; efficient procedures by contractors; better materials)

* Evolutionary, not revolutionary, approach (near-term usability; no esoteric systems)

* New approaches (such as high-pressure water instead of backhoes)

* Labor considerations (education/training in use of the technology; potential job losses)

* Life-cycle cost/benefits

* Political, as well as institutional and structural, barriers to acceptance of new technology

* Minimum initial cost (lowest initial cost drives new programs, not life cycle costs)

* Jobs

* Labor costs/quality

* Workers want better equipment, better man/machine interface (more done with less effort; systems must work well with real people)

* Leverage DoE, DoD, European, and Japan robotics programs

* Education/retraining (for enhancing labor pool)

* Equipment maintenance and repair (requirements for new systems)

* Demonstrate to contractor he can make money - give confidence in technology (can't be just marginally beneficial)

* Investment in R&D/technology by industry and government (require that advanced technology be used on projects; carrot better than stick?; cost sharing of technology demonstrations; encourage innovation with procurement of systems)

* Establish a network of stakeholders for this technology

* Need to reduce risk to initial users of new technology (capital risk; liability risk; how to spread risk equitably)

* Determine what makes the technology economic and attractive to users (such as improving the performance or cost of new workers; new people needed in the trade who can do a good job; contractors are concerned with *near-term* costs because they need to stay in business)

* Requirements to force use of robotic technology - driving forces (specifications which imply the use of certain technology, as in Japan where companies must show they invest in R&D in order to get contracts)

* Historical drivers are cost, safety, and health

* Not Invented Here (NIH) syndrome must be overcome

* Perhaps the U.S. should adopt European model: non-adversarial relationships; government, industry, and academia; partnering (but there are questions of scale - the U.S. has smaller construction companies than in Europe)

The plenary session will now generate a list of potential

opportunities, with respect to the introduction of robotics/automation for highway applications, for the working groups to consider:

* Use incentives (such as buy-back incentives where the government buys back old equipment, and subsidies for labor or equipment)

* Reduce hazards, which leads to savings in labor costs (working in trenches is hazardous; and falling is the main lethal accident in construction)

* Employ grade control (using automated measurement; materials oriented)

* Eliminate rollers and roller operators: compact behind the machine automatically in one pass instead of two or three; eliminate at least one roller operator)

* Eliminate handwork, such as raking, which leads to injuries

* Use quick methods of maintenance, such as patching, pavement repairs, and bridge painting to reduce traffic jams and public inconvenience

* Develop early maintenance procedures, such as non-destructive evaluation (NDE) capabilities to correct flaws before they get big

* Plan ahead

* Improve materials and emplacement techniques

* Improve traffic management and control during maintenance and repair (50% of the repair budget is spent on traffic management during repair)

* Improve data flow with management and project information systems

* Integrate traffic control with <u>all</u> jobs that need to be done at one time (i.e., take a systems approach)

* Extend/integrate computer-aided manufacturing techniques into road construction, maintenance, and operations

* Make systems user friendly (a major concern)

* Design appropriate standards and specifications (tradeoffs between innovation and open systems; have an innovation acceptance process)

* Incorporate GPS into robots and equipment for position determination on the job site (determining where equipment is located on a job site can be costly)

* Examine far-term (10-20 years) technology, support academic research and development

* Examine safety issues for robots, such as the ability of humans and robots to work safely in the same workspace (there's little past experience), and fail-safe behavior for the robots

After the five working groups discussed the various requirements, opportunities, and issues, they returned to the plenary session and briefed the Workshop on their recommendations.

Working Group 1

Recommendations by Working Group 1 included:

* Using robotics for further compaction at longitudinal joints (to seal the joints and increase the life of the pavement)

* Develop an alternative to excavation, or material removal, in traffic

* Develop computerized asbuilt, scheduling, etc., to have an integrated system, a total information process

* Develop positional control of equipment and tools

* Establish operational demonstration programs for new technology and share risks with equipment developers: the federal government should lend equipment to the contractor; then as technology becomes more accepted, the government should lease the equipment to the contractor; finally, the manufacturer sells the equipment to the contractor

* Emphasize teleoperation in the near-term, but some level of autonomy is needed to increase efficiency

* Avoid very specialized equipment

* Change the process, rather than simply automating the existing process

* Establish a long-range R&D program

* Integrate DoD and DoE robotics/automation technology into current DoT R&D process

* Use foreign technology as appropriate

* Canvass the private sector for other technology applications

Comments:

* There are already mechanisms in place for industry to share risks with government, such as the Cooperative Research And Development Agreement (CRDA).

* Evolution (instead of revolution) of new technology is not the only path - the Xerox machine did not evolve from carbon paper.

Working Group 2

Working Group 2 suggestions include:

* Involve labor in technology development (for example: the bricklayer's union is in favor of technology and automation, but they want to be involved in the introduction of the technology on the site)

* Automate the worker training process

* Assess road and bridge conditions using NDE (non-destructive evaluation) techniques, preferably in real-time

* Automate the detection of personnel, equipment, and material, for collision avoidance

* Automate materials management, to locate materials (which reduces waste) and enable night-time (or limited visibility) operations

* Automate traffic management (replacing the flagman and ensuring traffic stays outside the worksite)

* Justify using and investing in a new technology with value engineering and life-cycle costing (show how the technology contributes to life-cycle benefits, not just the initial costs)

* Introduce mechanisms in the contracting process to promote innovative technology (low bidder criteria discourages new technology because the company cannot recoup the investment cost)

* Develop mechanisms to evaluate innovations

* Introduce performance incentives to justify expenditures on new, innovative technologies

* Encourage industry/government/academia partnering

Comments:

* The mind set in the U.S. needs to change. The U.S. cannot simply adopt the European cooperation model because we have a different society. The form of the suggested partnering needs to be determined.

* The highway field can look to explorations of partnering by the building construction industry. Also, some states are engaging in partnering in road construction.

Working Group 3

Working Group 3 focused on the following problems:

* Low cost bid gets the job

- This tends to shunt aside new technology. In the U.S., the contractors are too small; perhaps small companies should merge (or perhaps this will happen as natural progress). Perhaps smaller companies can share expensive equipment (perhaps through leasing arrangements).
- The bidding structure should be renovated to favor new technology.

* Safety

- Traffic control through construction sites is needed. Consider: portable, mobile, automated speed bumps; or optimum detours across jurisdictional boundaries (to reduce driver frustration); or defensive radar with double penalties.
- Safety is labor intensive; new technology can reduce wasted time and labor.

* Technology transfer

- The technology needs CALTRANS type investment.
- Incremental introduction of new technology is less painful.
- Educate users - otherwise the technology won't get used.
- Government should orchestrate matched partnerships

* Regulation

- Simplify and reduce paperwork. For example, perform nuclear density testing at roadside; and with respect to asphalt content, certify plants, use process reports, and eliminate hazardous waste.

Comment:

* The problem is not the low bid system, but getting the technology into the bid. Initial costs must be overcome to gain the eventual benefit of less expensive operational or other costs (such as environmental costs).

Working Group 4

Working Group 4 considered the following needs:

* A database of automation projects in progress (perhaps generated at NIST). And get useful and motivational information to contractors, including cost and savings information. "We all want information."

* A listing of automation demonstrations - where and when.

* Working teams between contractor and administration, to ensure appropriate technology.

* Database of applicable technologies (such as ground-penetrating radar).

* Risk liability for R&D directed projects. (Who has the most risk, and how is risk shared)?

* Low bid mentality for value added automation projects.

* Top down input for projects; bottom up input for technology (contractors know what the problems are and what they want). Federal government should recommend projects. States should request bids with new technology included. Contractors should determine how to get new technology into proposal. Contractors should be part of the design phase of new technology.

Working Group 4 priorities for automation and robotics included:

* For bridges

 - Remote access
 - Remove humans from danger
 - Miniaturized equipment to operate in confined space and toxic atmosphere
 - Continuous on-line monitoring (load cells, acoustic emission, weight in motion)
 - Use of improved materials

* For traffic safety

- Traffic control (determine real hazards and best type of traffic control)
- Information about road repairs: imaging systems to find cracks, etc; preplanning before repairs to reduce time in the field, time for repairs, and public inconvenience.
- Educate the public about automation/robotics
- Use automation for backfilling of pipes

Working Group 5

Working Group 5 suggested:

* Performance-based specifications that would allow contractors to use proprietary materials and technology.

* Safety developments that reduce workplace hazards (whether contractor's employees or traveling public).

* Partnerships between government, academia, and industry, to focus on use of existing resources and technology. Historically, new technology has been introduced by state's mandating certain technology, or performance which required new technology to achieve.

FINAL PLENARY SESSION

After the presentations of the working groups, various recommendations culled from the various topics and issues were listed. Each attendee was given five votes, and asked to vote once for each of his or her top five priority choices. While the list consisted of a non-homogeneous, non-coherent, incomplete aggregation of issues and functional areas, it is a reasonable first-cut effort at bounding and partitioning the problem space. It is useful to see what a cross-section of the road construction community thinks is important, and there were clear demarcations of the topic priorities. The list follows, in priority order with the *number of votes in brackets* at the end of each item.

{1} Use lifecycle value engineering or performance-based specifications to provide incentives for automation and robotics innovations (such as designing structures or bridges for ease of later maintenance and repair; even if the initial cost is greater, the lifecycle cost could be less). [26]

{2} Use automation and robotics to reduce workplace hazards. [24]

{3} Develop a site positioning system (to determine what is on a site and where it is). [19]

{4} Use partnering to share costs and risks of innovation (including R&D). [15]

{5} Develop techniques for non destructive evaluation (NDE) and monitoring for bridges, pavements, locating utilities, etc. [13]

{6} Improve traffic control and reduce its costs (which can be 50% or more of a repair job) to highway department users. [12]

{7} Assemble a database of automation projects, demonstrations, and technologies. [12]

{8} Use automation and robotics for pavement maintenance and construction. [11]

{9} Use automation in the maintenance of bridges (there are 500,000 bridges in the U.S. and 25% are known to be structurally defective). [10]

{10} Design automation and robotics into the construction, maintenance, and retrofit process (i.e., concurrent engineering); to have repair-friendly designs for bridges, for example, so that a modified bridge structure could accommodate new technology using sensors, rails, etc. [9]

{11} Involve the labor force in the process to give them a stake in innovation (i.e., make labor a part of the solution instead of part of the problem). [7]

{12} Develop an "as built" (and "as maintained" and "as operated") integrated project information system. [7]

{13} Use automation and robotics to enhance the capabilities (i.e., increase efficiency) and reduce the cost of labor. [7]

{14} Use automation and robotics for trenching and ditching. [3]

{15} Use automation and robotics for demolition/recycling. [0]

While one might partition the results in various ways, it seems reasonable to assign recommendations {1}-{4} to the first rank of priorities; recommendations {5}-{7} (where {7} is at 50% of the top score for {1}) to the second rank; and recommendations {8}-{15} to the third rank.

According to the top four priorities, the automation and robotics program should take the broad systems approach to introduce the technology, stressing lifecycle value engineering for highway projects. While increased safety should be a major goal for the technology, a key initial application should be site positioning system. And government, industry, and academia should work together to develop and introduce the technology to the worksite.

Consensus For An Ongoing Process

After the plenary voting on recommendations, the workshop consensus was that there should be an ongoing process in which government, industry, and academia could work together to further the development and implementation of automation and robotics for road construction, maintenance, and operations, perhaps a structure analogous to what IVHS America does for the IVHS program. Other associations could be involved in an ongoing process, such as the Transportation Research Board, the Society of Automotive Engineers, and the Stone, Asphalt, and Concrete Pavement Associations. The Association For Unmanned Vehicle Systems offered to sponsor an Industry Support Group (ISG), similar to the ISGs it support for unmanned air and ground vehicles. Meanwhile, NIST will provide the coordinating function for ongoing working groups, and it will survey workshop attendees and other prospective participants for the groups.

Ernie Kent: Final Words

This has been an initial meeting in a series of actions - to touch base with the community familiar with highway construction, maintenance, and operations, and to give guidance to the process. We are also doing a literature search , forming panels of robotics experts for job site visits, and convening a technology-based workshop in conjunction with the National Science Foundation.

Output from this workshop and continuing consultation will give us an ongoing reality check. Out of the process will come a number of proposals which will undergo cost/benefit analyses before being submitted to the FHWA. The FHWA will then act on the findings.

Each attendee to this Workshop will get a copy of a report on the Workshop. We encourage you to act as a sounding board and give us suggestions to keep us on track, and continue to provide input into the process.

We have had a good beginning in this Workshop and some of our cherished views have changed, and that is all to the good. We need to have the technologist's views changed in many instances by the people who are out there where the work is going on. This is crucial to the process.

Thank you for your time, your effort, and your input.

APPENDIX A

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APPENDIX B

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APPENDIX C

DR. RICHARD WRIGHT: CHARTS

AUTOMATION AND ROBOTICS

FOR

HIGHWAY DESIGN, CONSTRUCTION, OPERATION AND MAINTENANCE

OBJECTIVES

- DEFINE THE FUNCTIONAL NEEDS THAT CAN BE MET BY AUTOMATION AND ROBOTICS
- DEFINE TECHNOLOGICAL DEVELOPMENTS REQUIRED TO MEET THESE NEEDS
- DEFINE ORGANIZATIONAL AND INSTITUTIONAL CHANGES NEEDED TO EXPLOIT AUTOMATION AND ROBOTICS FOR HIGHWAYS

PROGRESSION OF INNOVATION

- EXISTING PRODUCT OR PROCESS REPLACED WITH INNOVATION
- PRODUCT OR PROCESS MODIFIED TO EXPLOIT POTENTIAL OF INNOVATION
- ROLES AND RESPONSIBILITIES MODIFIED TO FIT THE NEW ENVIRONMENT

REQUIREMENTS FOR HIGHWAY SYSTEMS PERFORMANCE

- ECONOMY (LIFE CYCLE PERSPECTIVE)
- FUNCTIONALITY
- DURABILITY
- TIME SAVINGS
- SAFETY
- ENVIRONMENT
- REGULATORY COMPLIANCE

OPPORTUNITIES IN AUTOMATION AND ROBOTICS

- MEASUREMENT AND SITE DATA ACQUISITION
- AUTOMATION OF QUALITY ASSURANCE AND INSPECTION
- MATERIALS HANDLING AND MANAGEMENT
- EARTH MOVING, FABRICATION, PLACEMENT, FINISHING
- INTEGRATED PROJECT INFORMATION SYSTEMS
- PROJECT MANAGEMENT
- OPERATIONS, MAINTENANCE AND REPAIR

APPENDIX D

DR. LEONHARD BERNOLD: CHARTS

AUTOMATION OVERVIEW

Presentation to the Workshop on
<u>Automation for Road Construction, Maintenance and Operations</u>

Sponsored By The Federal Highway Administration
Hosted By The National Institute of Standards and Technology

by

Dr. Leonhard E. Bernold
Associate Professor
Department of Civil Engineering
North Carolina State University

Director
Construction Automation and
Robotics Laboratory

Gaithersburg, Maryland
November 4, 1992

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(ONE) DEFINITION FOR AUTOMATION

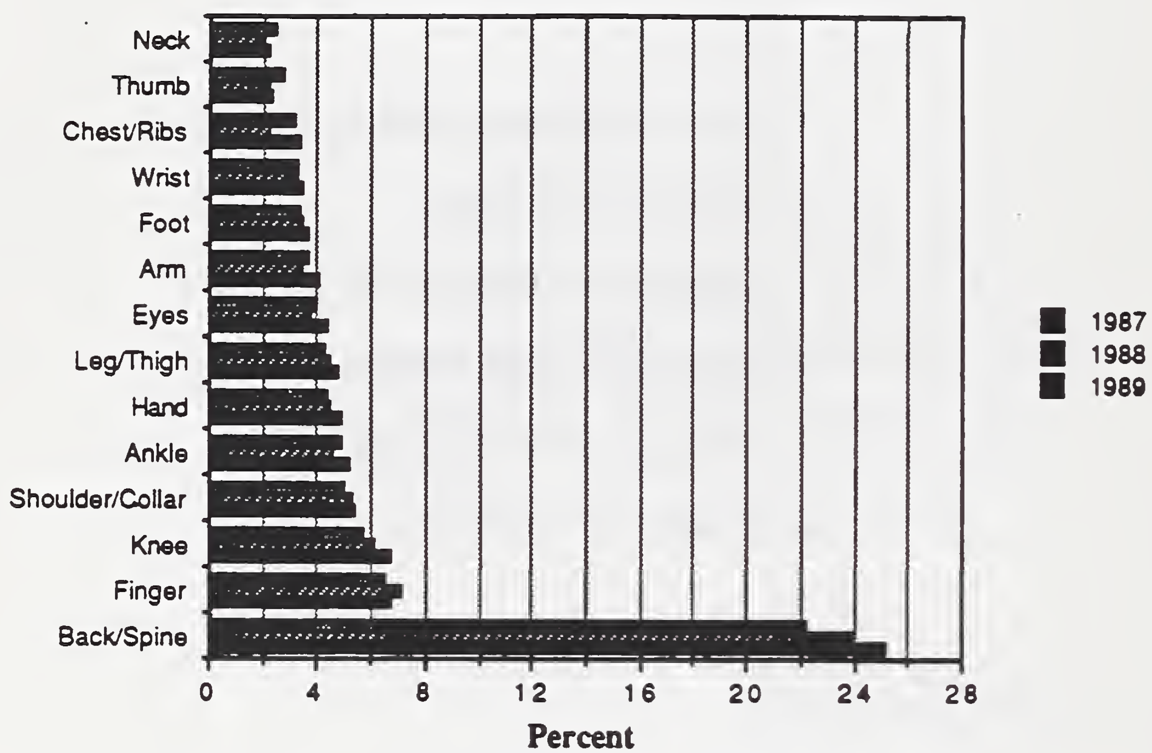
"... a technology that is concerned with the use of mechanical, electronic, and computer-based systems in the operation and control of production."

in Industrial Robotics
by Groover, Weiss, Nagel, Odrey

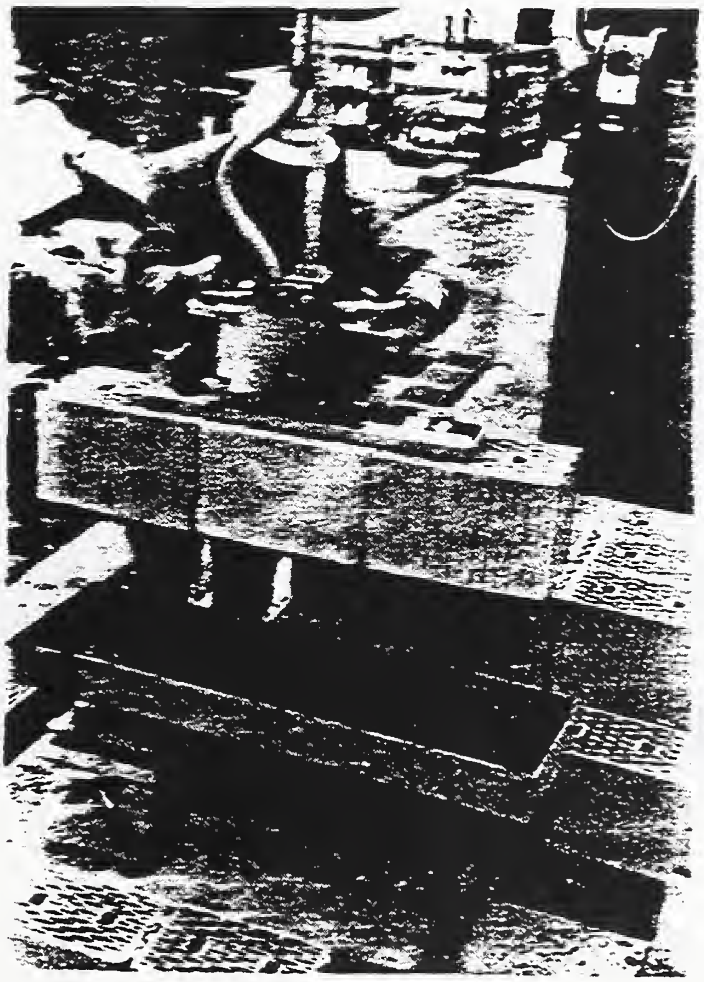
MOTIVATON TO AUTOMATE

1. Safe and Humane Workplaces
2. Reduction of Waste
3. Support for Human Workers
4. Consistent High Quality
5. Increase of Productivity
6. Benefits to Mankind
7. ...

BACK INJURIES IN CONSTRUCTION



THE MASON'S MECHANICAL SLAVE
(Germany)



FIRST THINGS FIRST

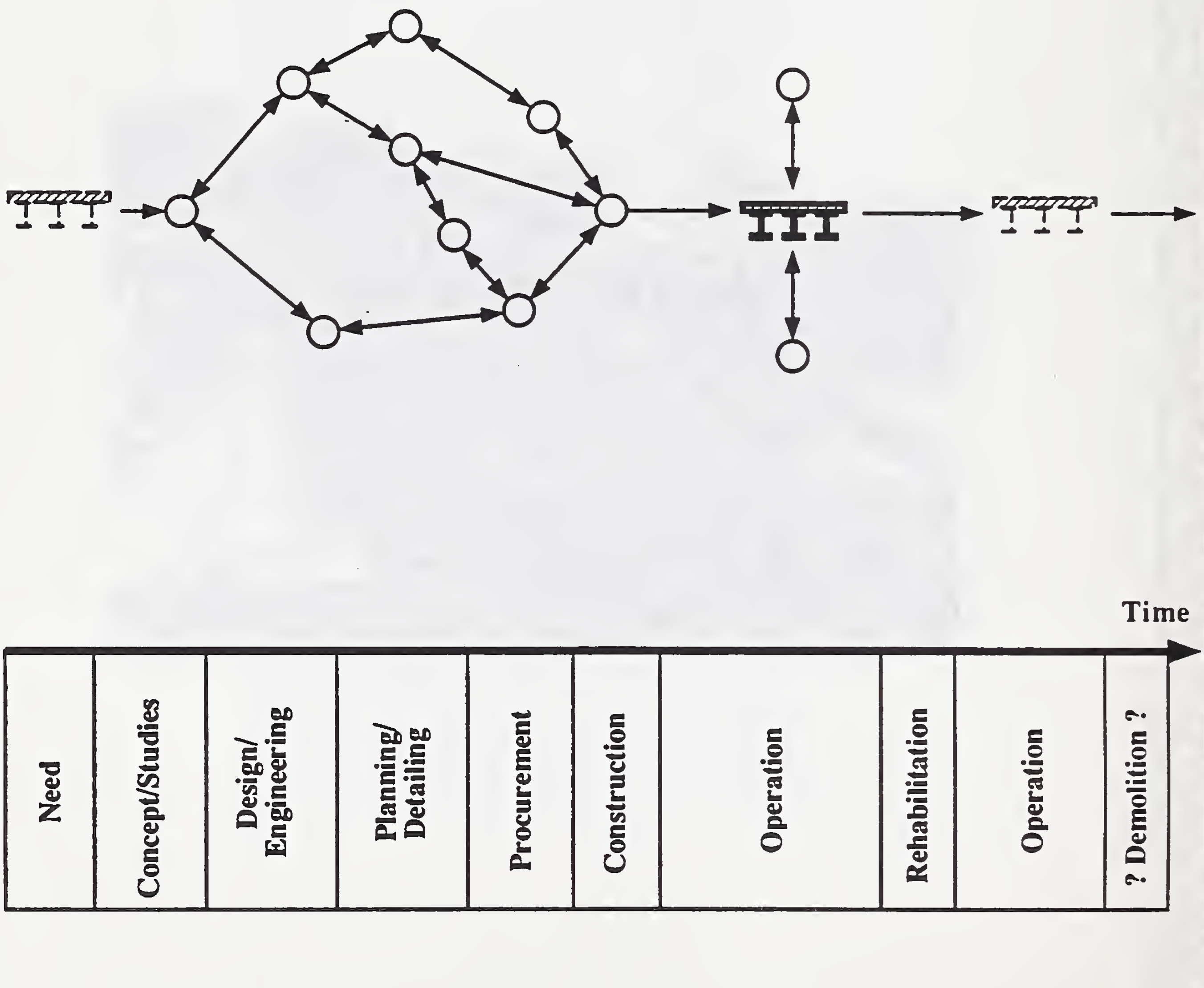
"If you automate a plant that is a mess,

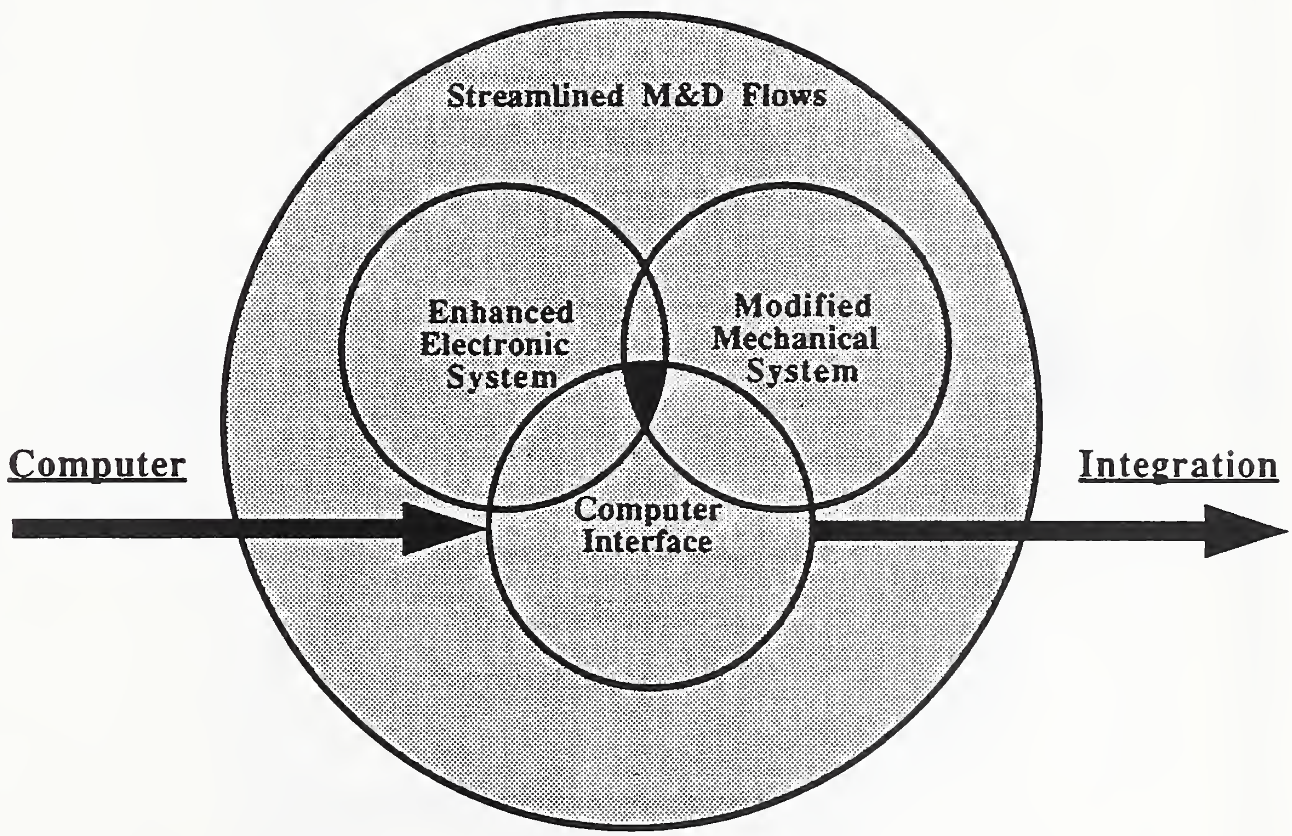
you should expect an automated mess."

Bob Stansell of Luck Stone, Inc.

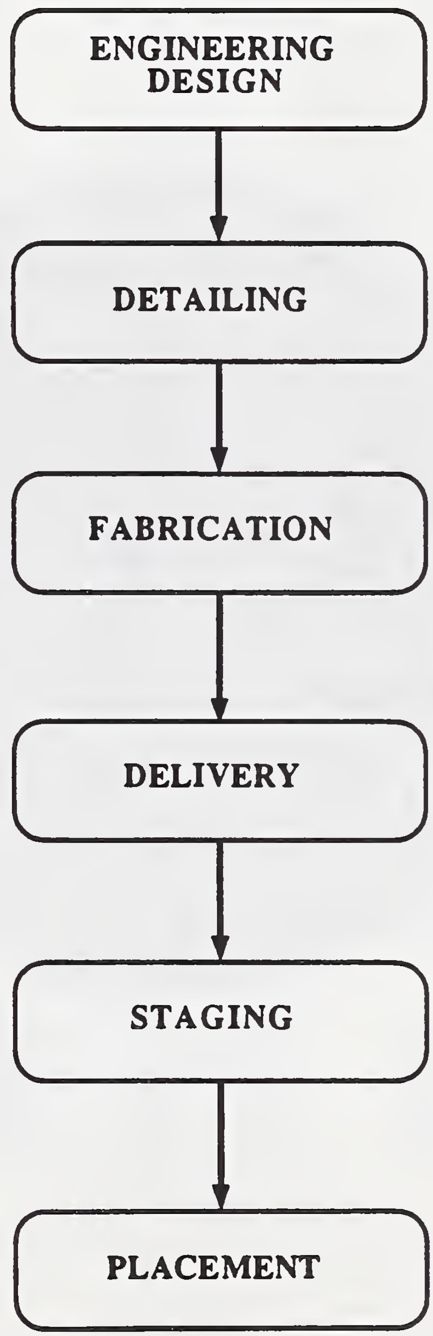
COMMON PRACTICE OF PLACING REBAR

LIFE-CYCLE OF DATA AND OBJECTS OF CONSTRUCTION

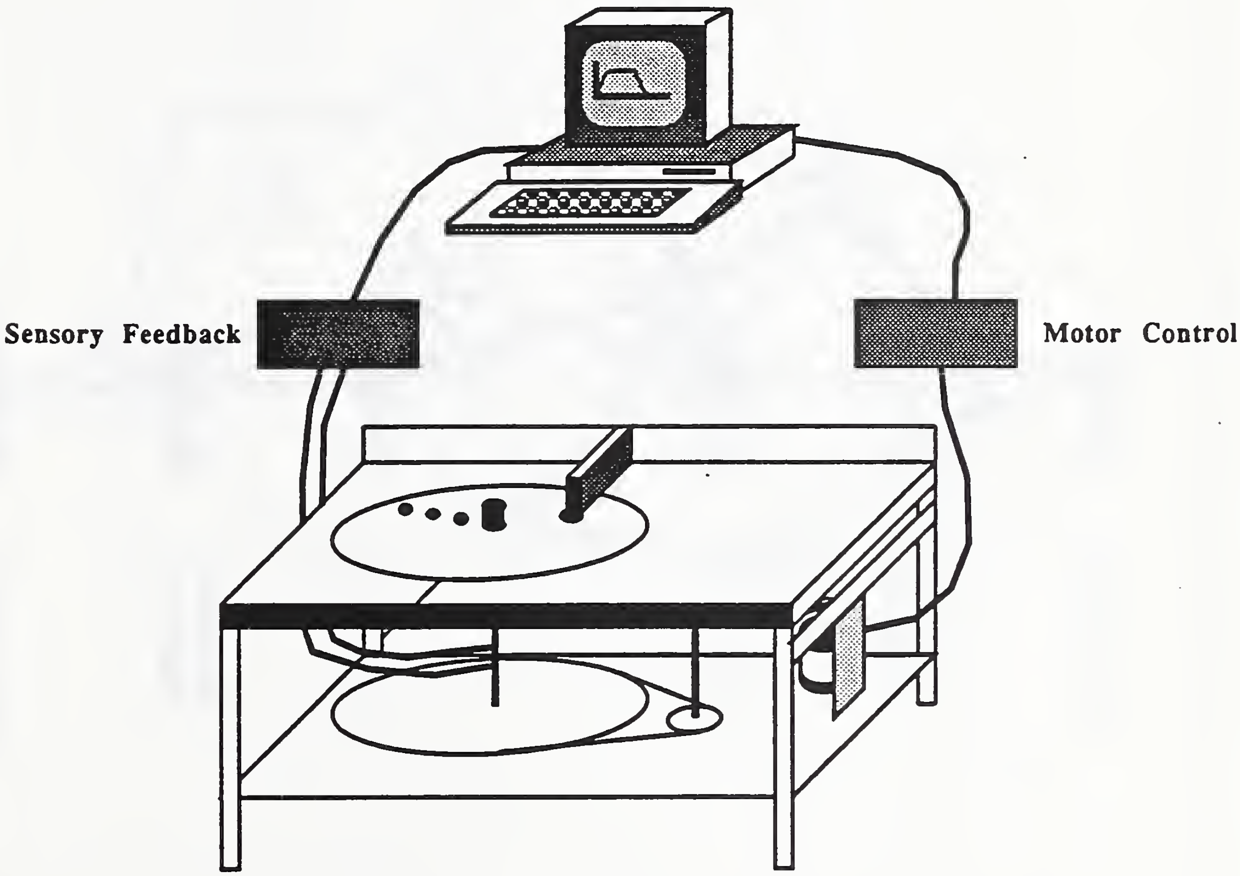



Streamlined M&D Flows
Enhanced Electronic System
Modified Mechanical System
Computer Interface
Computer
Integration

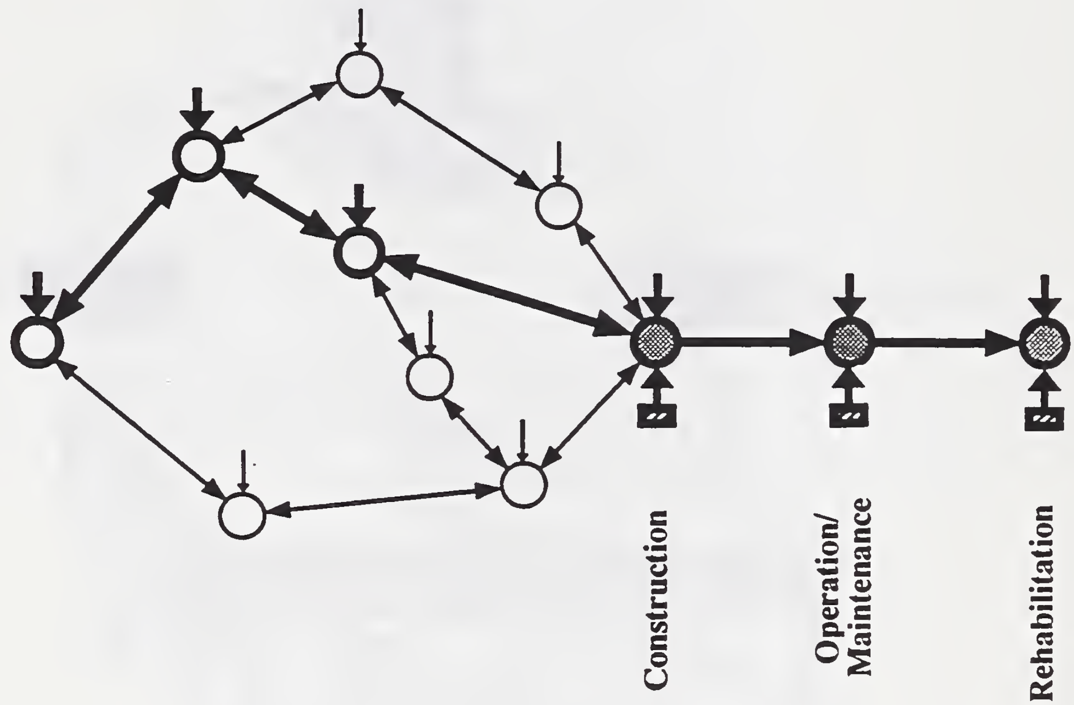
REBAR IN CONCRETE CONSTRUCTION



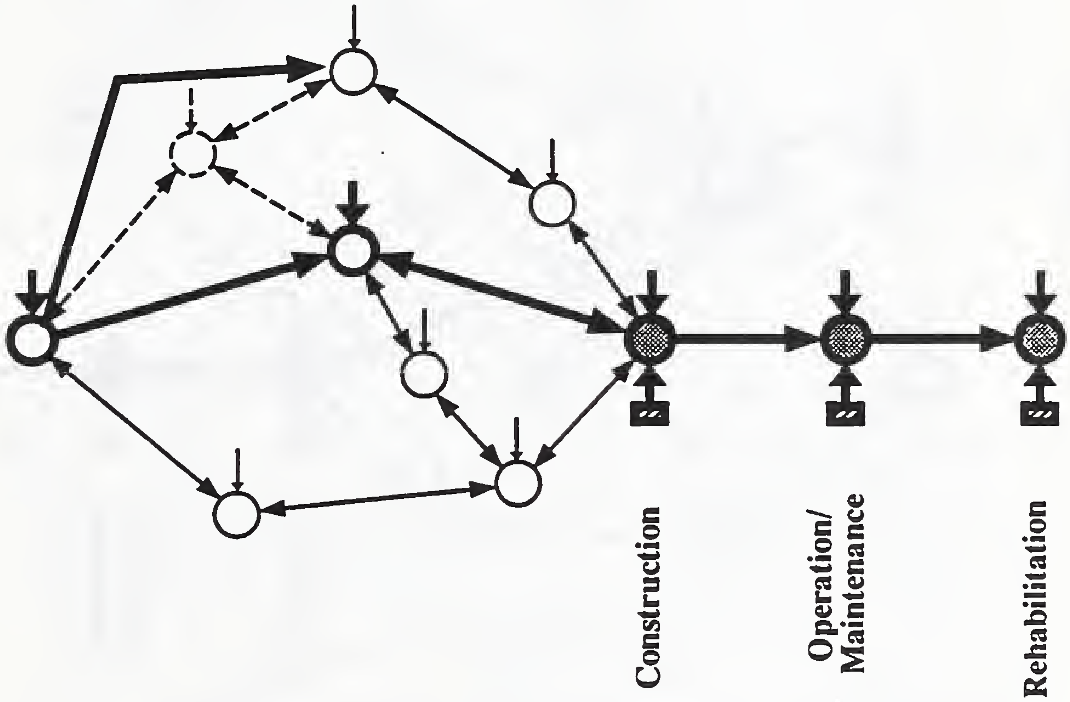
AUTOMATION OF REBAR BENDING



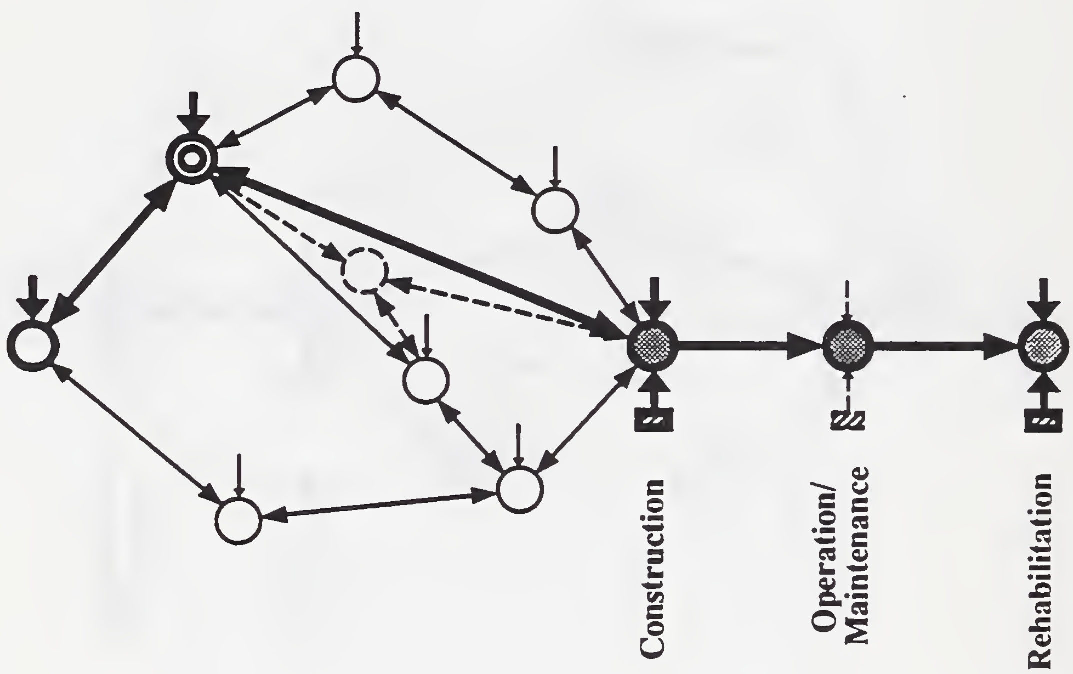
ELECTRONIC DATA FLOW



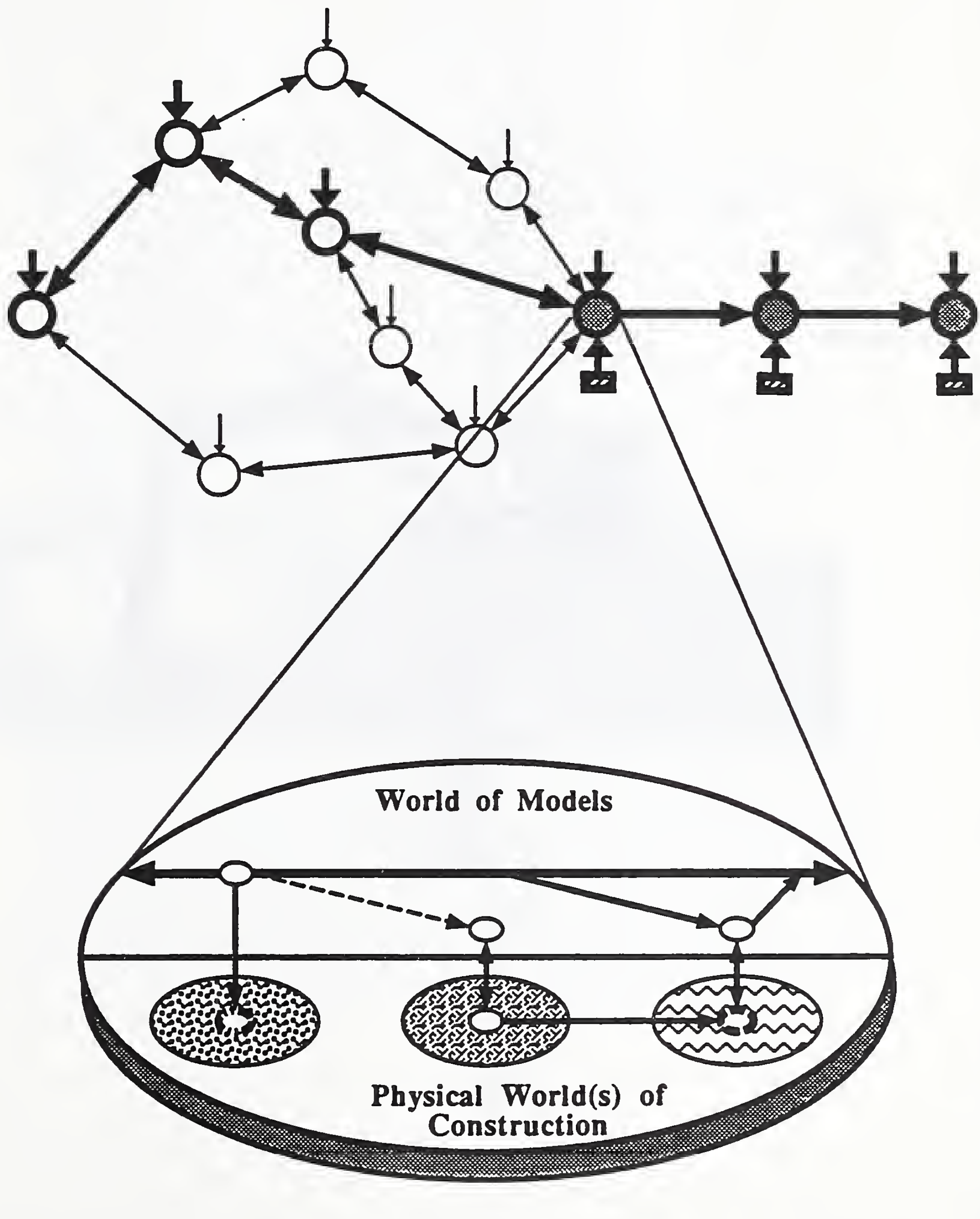
COMPUTER AIDED DESIGN AND DRAFTING



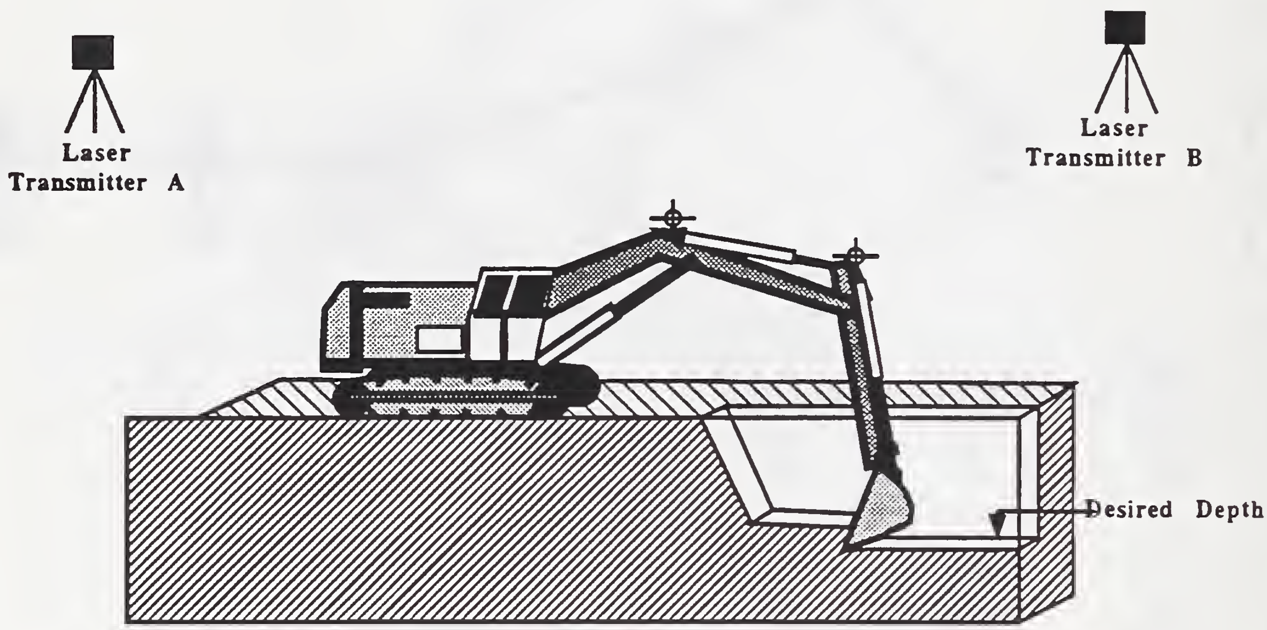
AUTOMATED PROCESS PLANNING



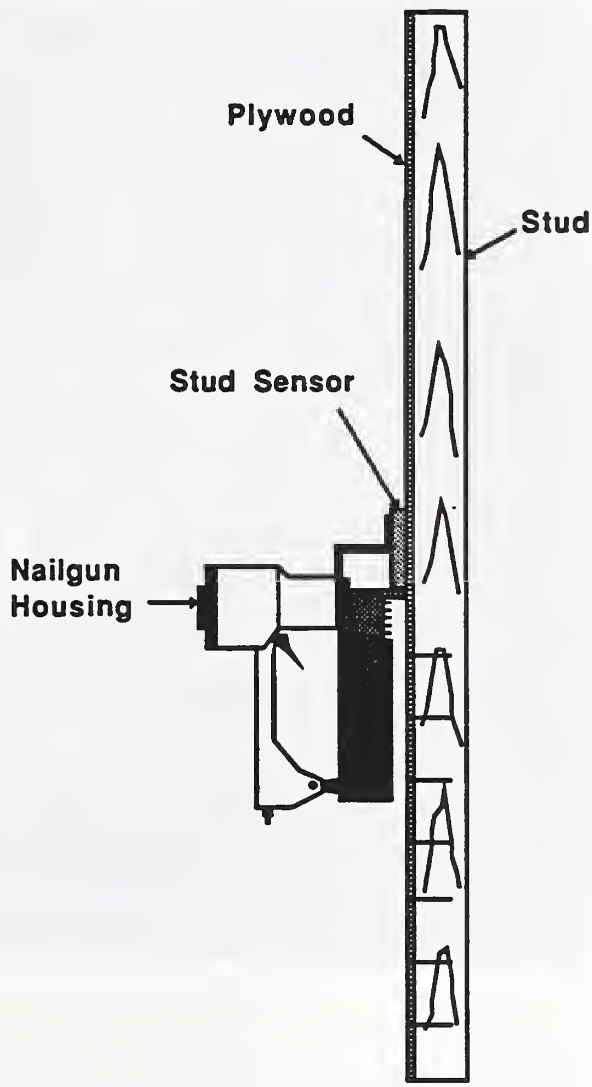
THE CHALLENGE OF SITE AUTOMATION



LARGE MANIPULATORS
(Excavators)

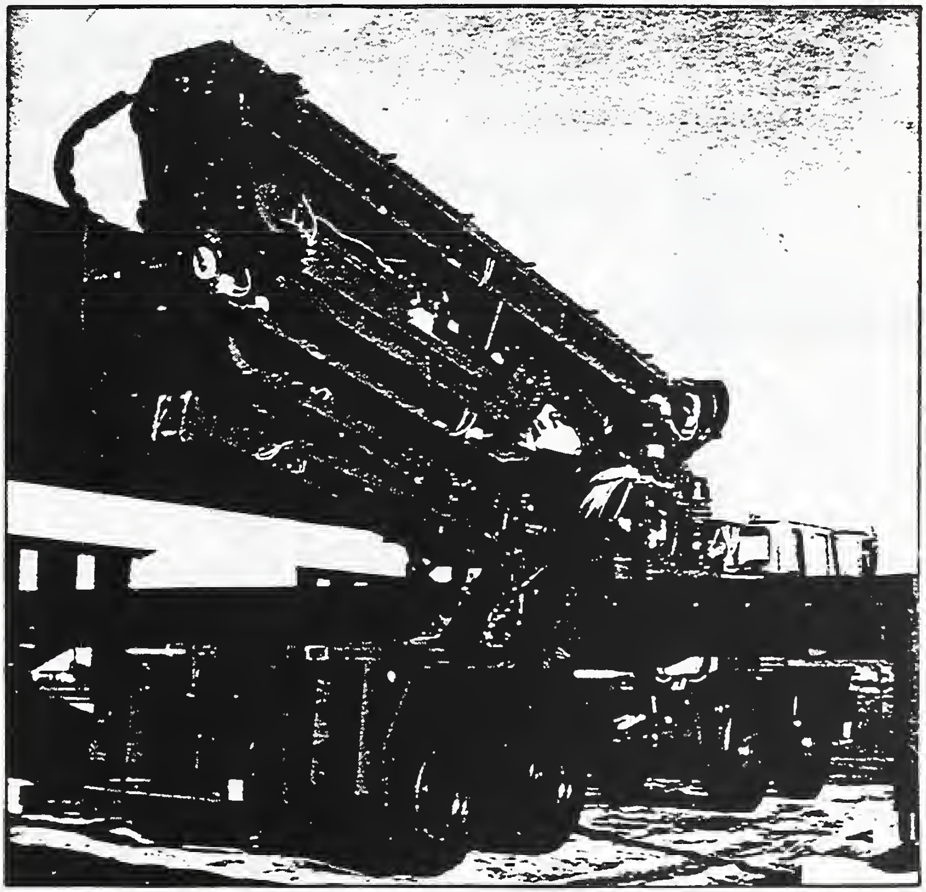


A SMART NAILER

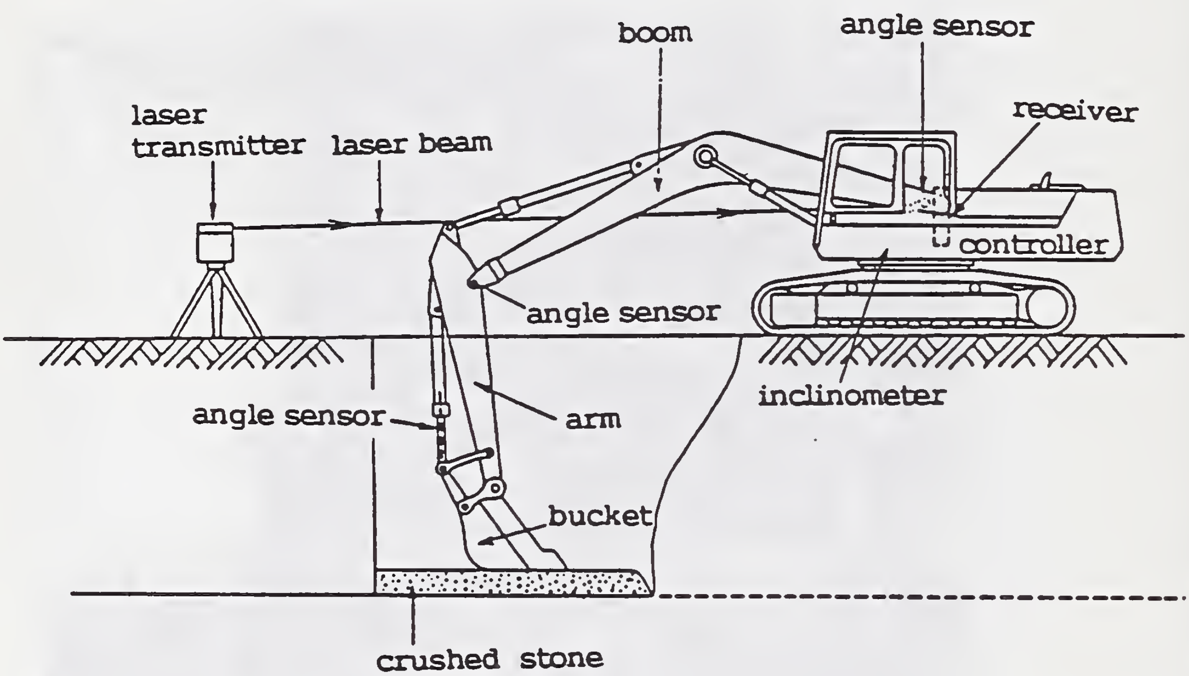


WASTE REDUCTION

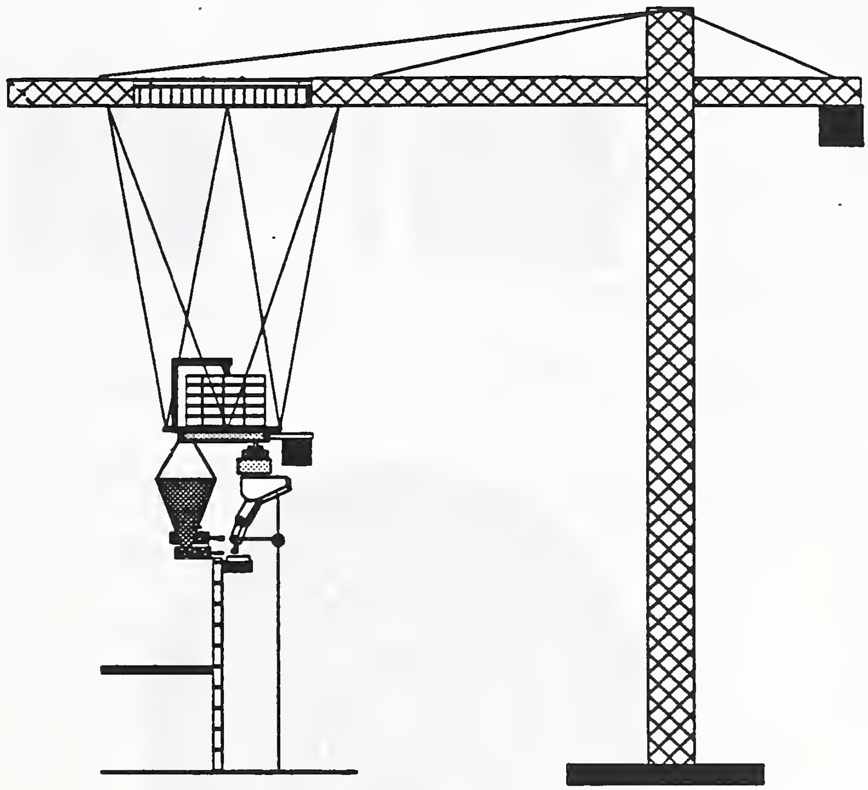
LARGE MANIPULATORS
(Germany)



LARGE MANIPULATORS
(Japan)



LARGE MANIPULATORS
(Cranes)



AUTOMATED DATA ENTRY
(Bar Codes)

55

23

3146

3146

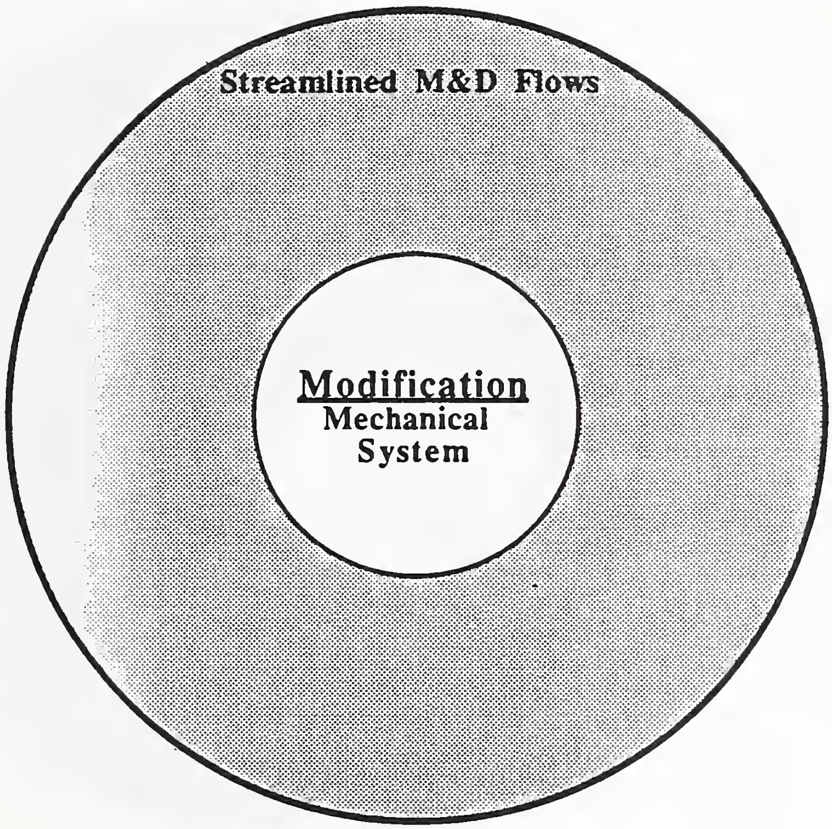
3146

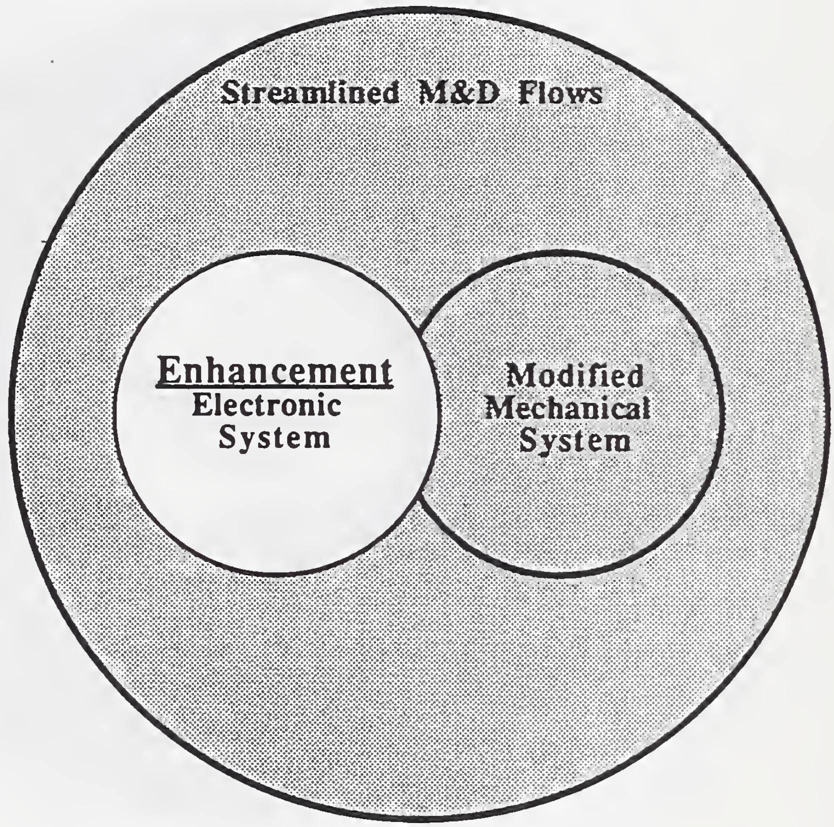
3146

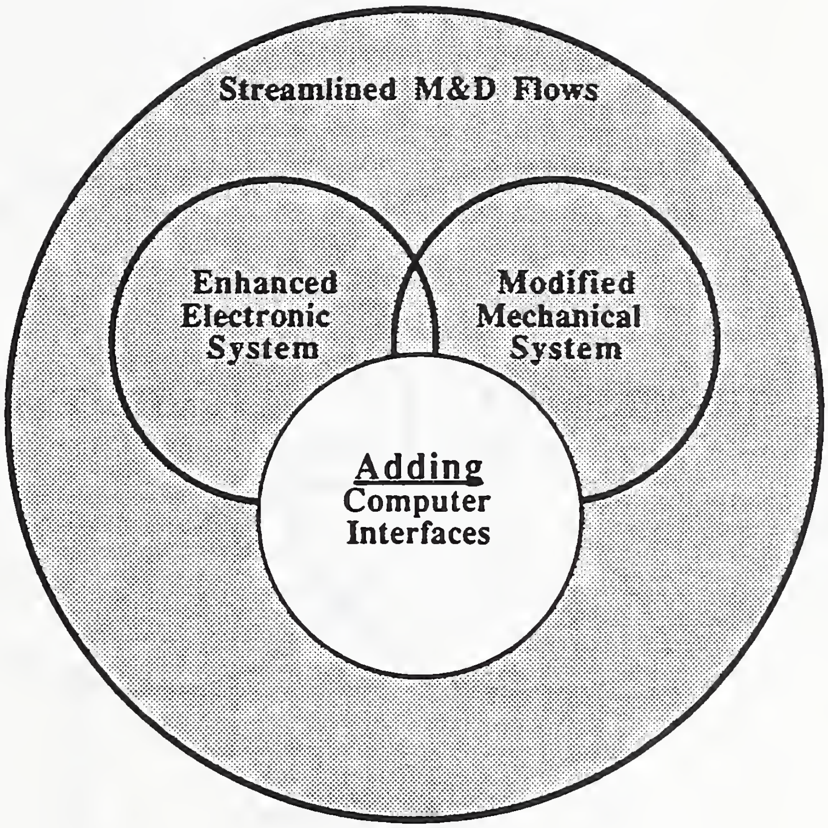
AUTOMATED DATA ENTRY
(Speech Recognition/Pen)

		SOUND RECOGNITION DATA BASES		
OBJECTS	LEXICON OF CODE NAMES (WORDS)	User 1	User 2	User 3
	Skilsaw			....
	Circular Saw			....
	Handsaw			....
	etc.			
	Georgia Buggy			
	Buggy			
	etc.			

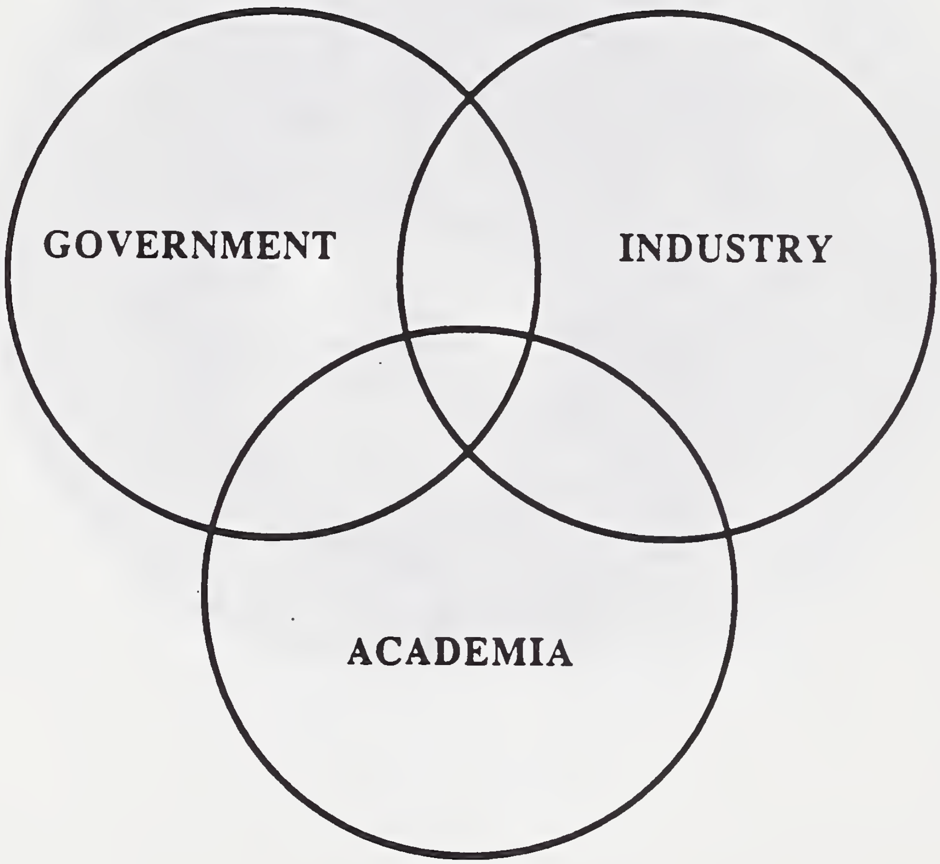
BOTTOM-UP APPROACH TO PROCESS AUTOMATION


Streamlined M&D Flows
Modification
Mechanical
System


Streamlined M&D Flows
Enhancement
Electronic
System
Modified
Mechanical
System


Streamlined M&D Flows
Enhanced Electronic System
Modified Mechanical System
Adding Computer Interfaces

COMPETENCE, COMMITMENT AND EFFECTIVENESS



HOPE

Second marriage: The triumph of hope over experience.

Samuel Johnson

APPENDIX E

MR. THOMAS PASKO: CHARTS

OFFICE OF ADVANCED RESEARCH (HAR-1)

Thomas J. Pasko

Secretary - (Vacant)

OPERATIONS RESEARCH DIVISION

Mr. James Wentworth

Dr. M. Oskard

PHYSICAL RESEARCH DIVISION

Mr. Charles Niessner

Dr. C. Ormsby

Mr. Charles McGogney

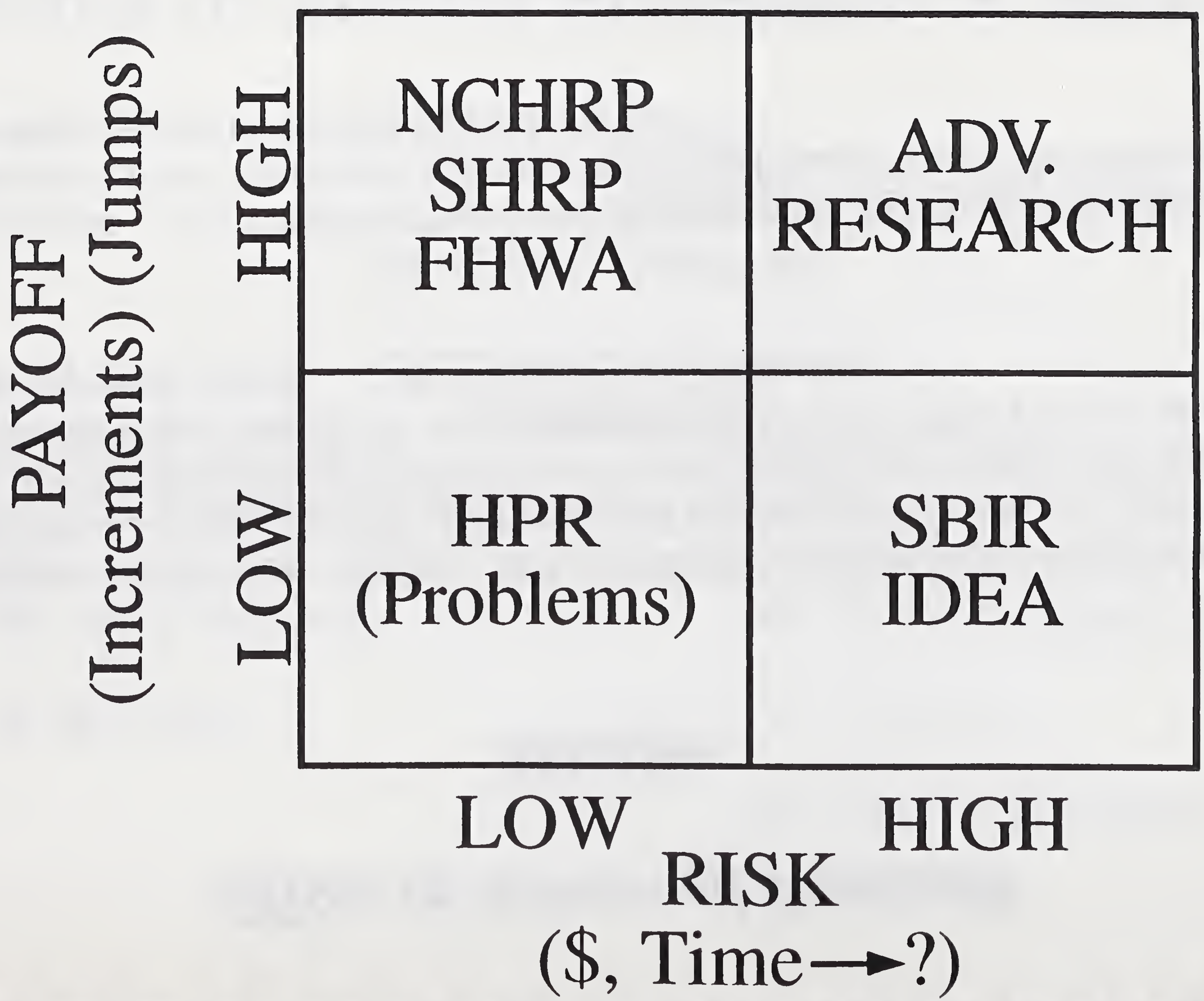
Dr. D. C. Woo

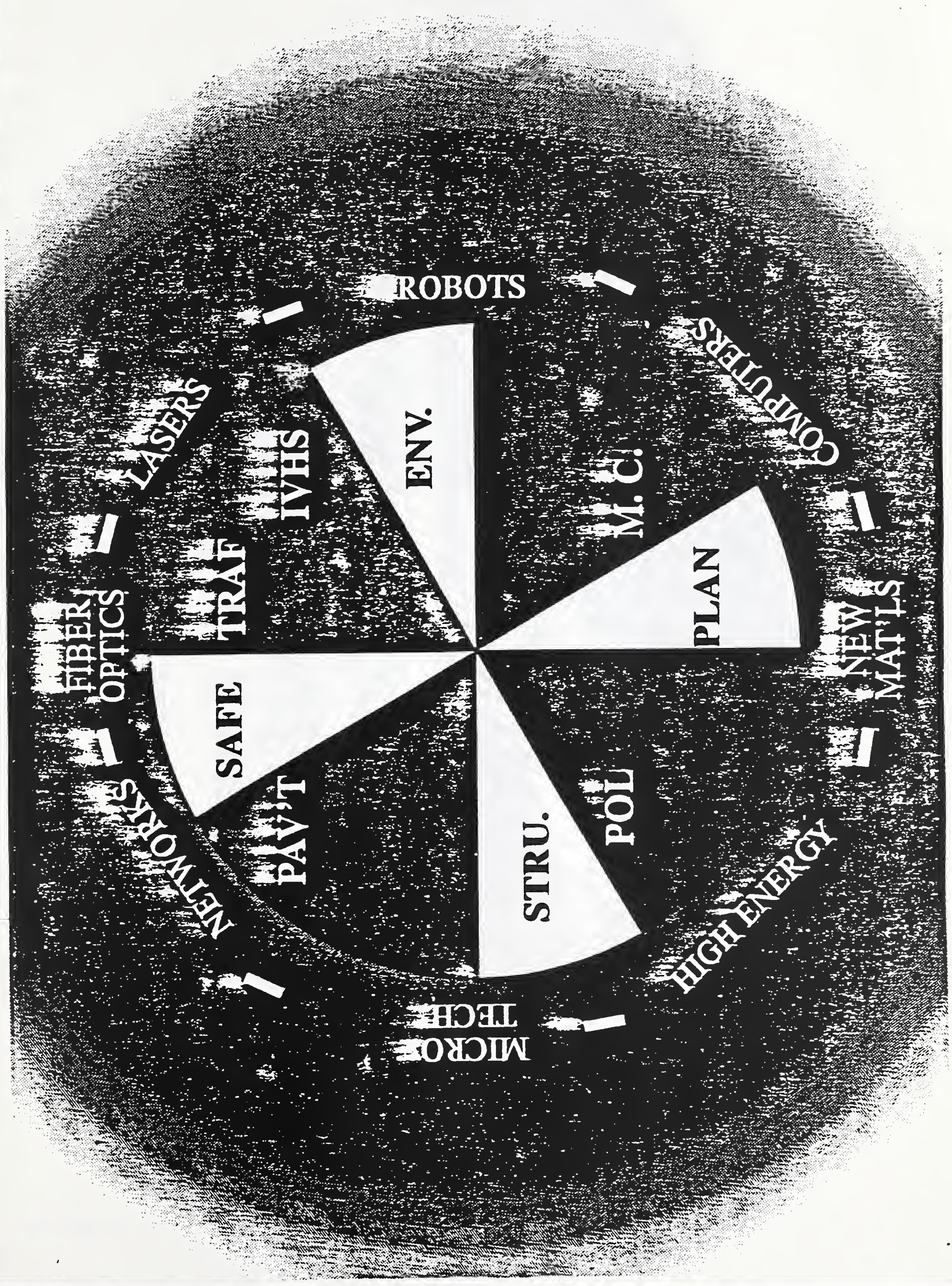
Office of Advanced Research

Mission

"To plan, administer, conduct, and coordinate fundamental research and <u>innovative adaptations for emerging and advanced</u> technologies which have potential for long range applications in the highway program. The research and technology adaptation is <u>coordinated with</u> NAS, NSF, Federal and State agencies, [etc], --- <u>international and domestic</u> ---

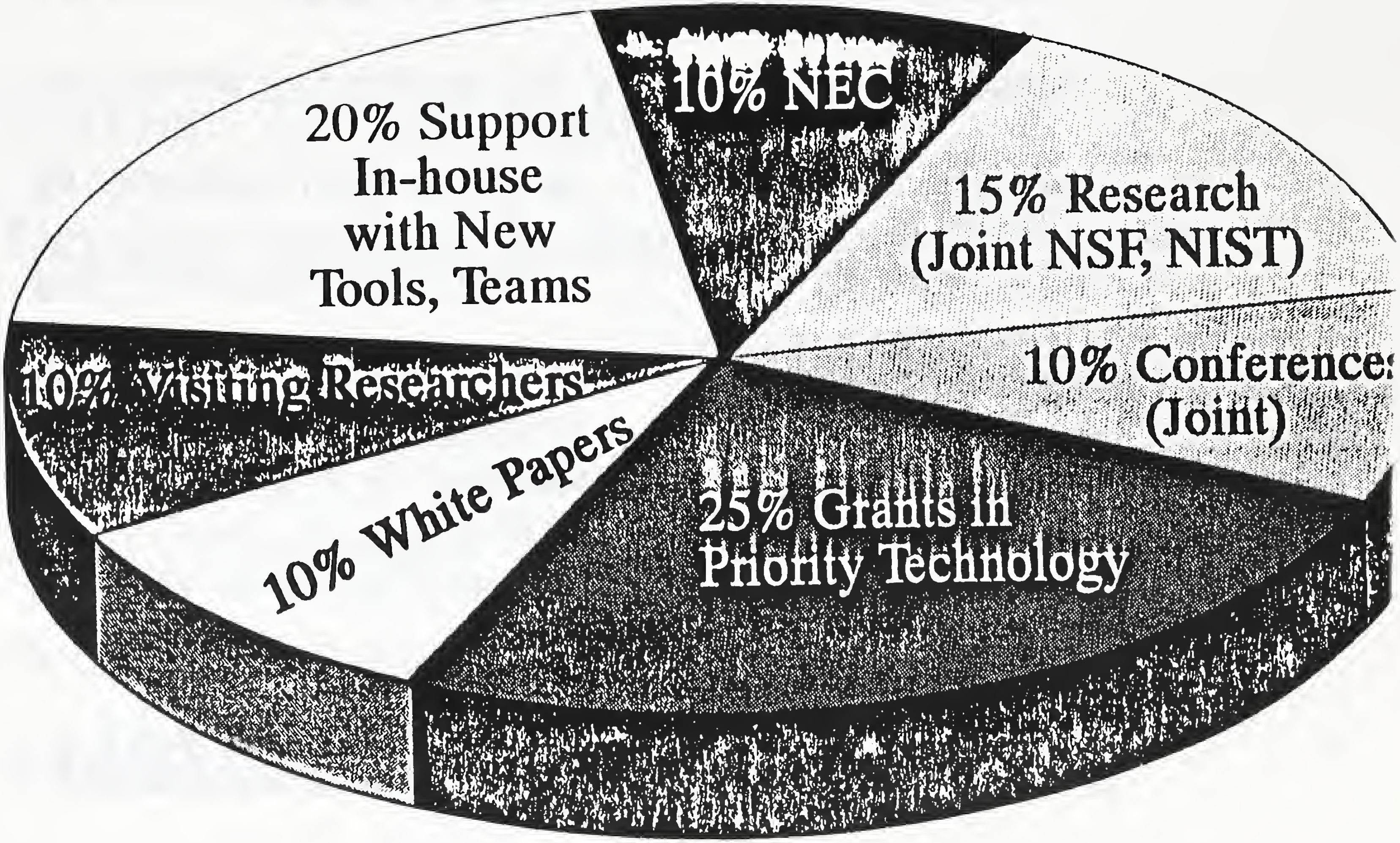
The results -- are further refined and <u>developed in the applied research</u> programs of the Associate Administrator for Research and Development -- and other applied research organizations --"


PAYOFF
(Increments) (Jumps)
HIGH
LOW
NCHRP
SHRP
FHWA
ADV.
RESEARCH
HPR
(Problems)
SBIR
IDEA
LOW
HIGH
RISK
($, Time→?)


ROBOTS
COMPUTERS
NEW MAT'LS
HIGH ENERGY
MICRO TECH
NETWORKS
FIBER OPTICS
LASERS
ENV.
M. C.
PLAN
POL
STRU.
PAV'T
SAFE
TRAF
IVHS

ACTIVITIES

1. Visiting Researchers Program
2. Innovator's Front Door
3. Grants for Advanced Technologies
4. Conference with Position Papers
5. Key Contract Gap Filling
6. Co-funding (NSF, NIST, etc)
7. Technology Scans Here/Abroad
8. Internal Teams/Circles


10% NEC
20% Support In-house with New Tools, Teams
15% Research (Joint NSF, NIST)
10% Conferences (Joint)
10% Visiting Researchers
10% White Papers
25% Grants In Priority Technology

VISITING RESEARCHERS

1PA	Prof. Lee, Iowa, 7/1, 1 yr	Asphaltic Mixtures
	Prof. Flood, MD, 7/1, Summers	Neural Networks
IRF	Prof. Ouyang, China, 9/1, 1 yr	Geosynthetics
	Prof. Liao, China, 9/1, 1 yr	Tiebacks
NRCPD	Dr. Schueller, UVA, 9/1, 2 yrs	Basic Corrosion
	Dr. Stewart, MT State U, 9/1, 2 yrs	Basic Asphalt
	Dr. Huong, CCNY, 1/1, 2 yrs	Basic Deicers
	T.B.D. Pending, 2 yrs	Surface Energy

I. National Service Center (Niessner)

II. Decision Analysis in Transportation (Oskard)

III. Energy and Conservation Related Technology (Ormsby)

IV. High Performance Materials (Pasko)

V. Self-Monitoring Systems (McGogney)

VI. Robots/Automation/Man-Machines (Woo)

VII. Computer Driven Technologies (Wentworth)

I National Service Center (Niessner)

- Entry Door for Innovators
- Coordinated Evaluation Efforts
- Contractor Operated - $1M/yr
- Time and $ Savings for Applicants/Users
- Workshop September 1992
  - FHWA/CERF/TRB/AASHTO/C of E
  - Develop Center Concepts

II. Decision Analysis in Transportation (Oskard)

- Optimization Methods in Planning R&D
- Phenomenological Approach to Problems
- Neural Networks
- Multi-Criteria Decision Methods
- Nonlinear Finite Element Methods
- Investment Analysis (Life-Cycle Costs)

III. Energy and Conservation Related Technologies (Ormsby)

- Upgrading Materials via Chemical Treatment
- High Temperature Materials Processing
- Laser Fused Surfaces
- All Weather Roads
- New Cements
- Institutional/Environmental/Safety Issues

IV. High Performance Materials (Pasko)

- COMAT (interagency)
- CERF/AISI/ACI
- Optimized Prototype Structures
- Minimize Quantities,
  Lighter/Longer Structures
  Composite Action
- Institutional Issues

V. Self-Monitoring Systems (McGogney)

- Multi-property NDE Scanning
- Global NDE
- Sensors/Communications/Systems
- SMART Materials
  - Sensors
  - Visual Warning
  - Reactive (Repair)
- Inspection

VI. Robots/Automation/Man-Machine (Woo)

- Production
- Construction
- Maintenance
- Continuous Quality Control
- Hazardous Environment

VII. Computer Driven Technologies (Wentworth)

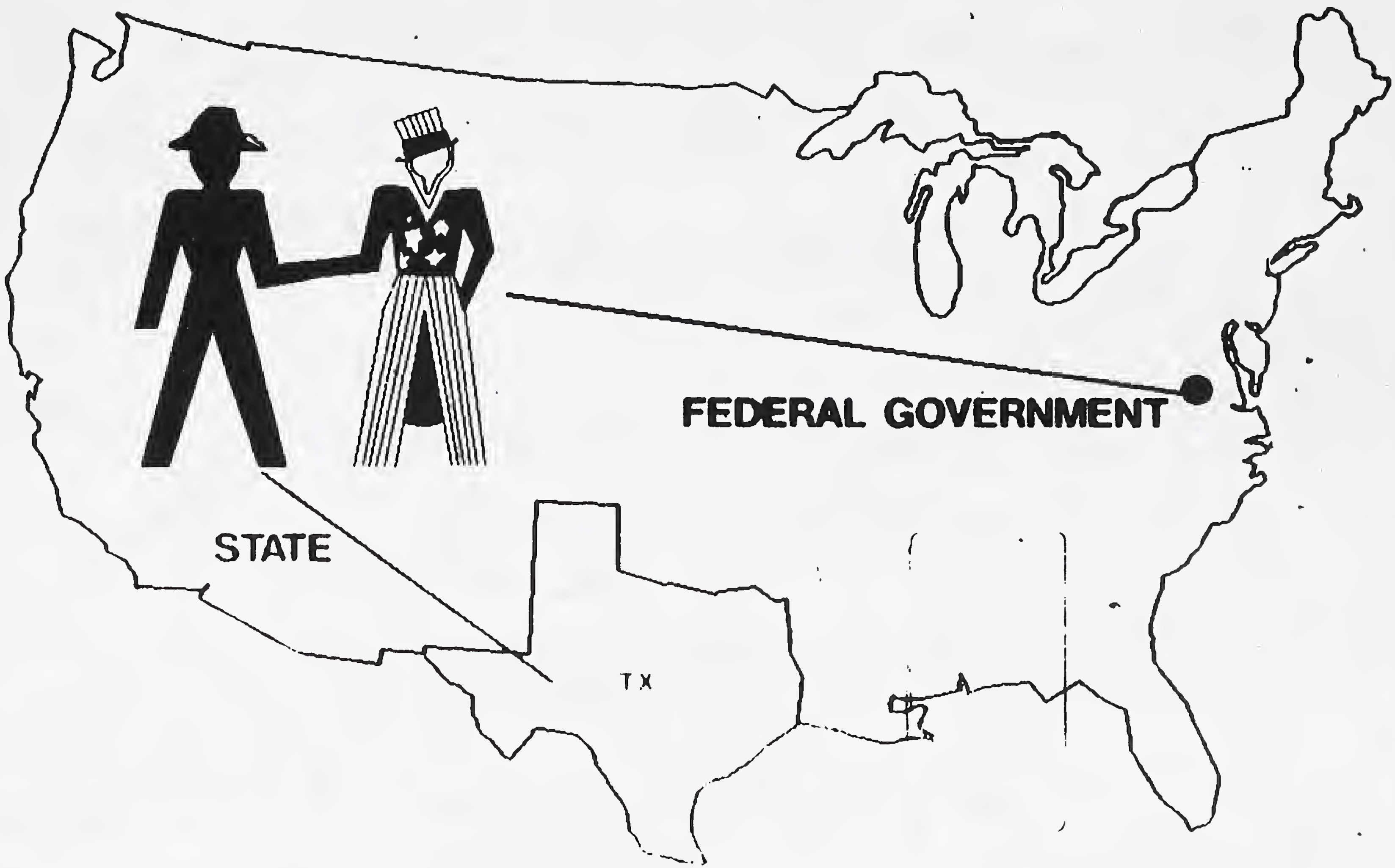
- Expert Systems/Fuzzy Logic
- Machine Vision/Voice Synthesis
- Advanced Communications/Computer Systems
- Statistical/Computational Methods
- Artificial Intelligence Circle

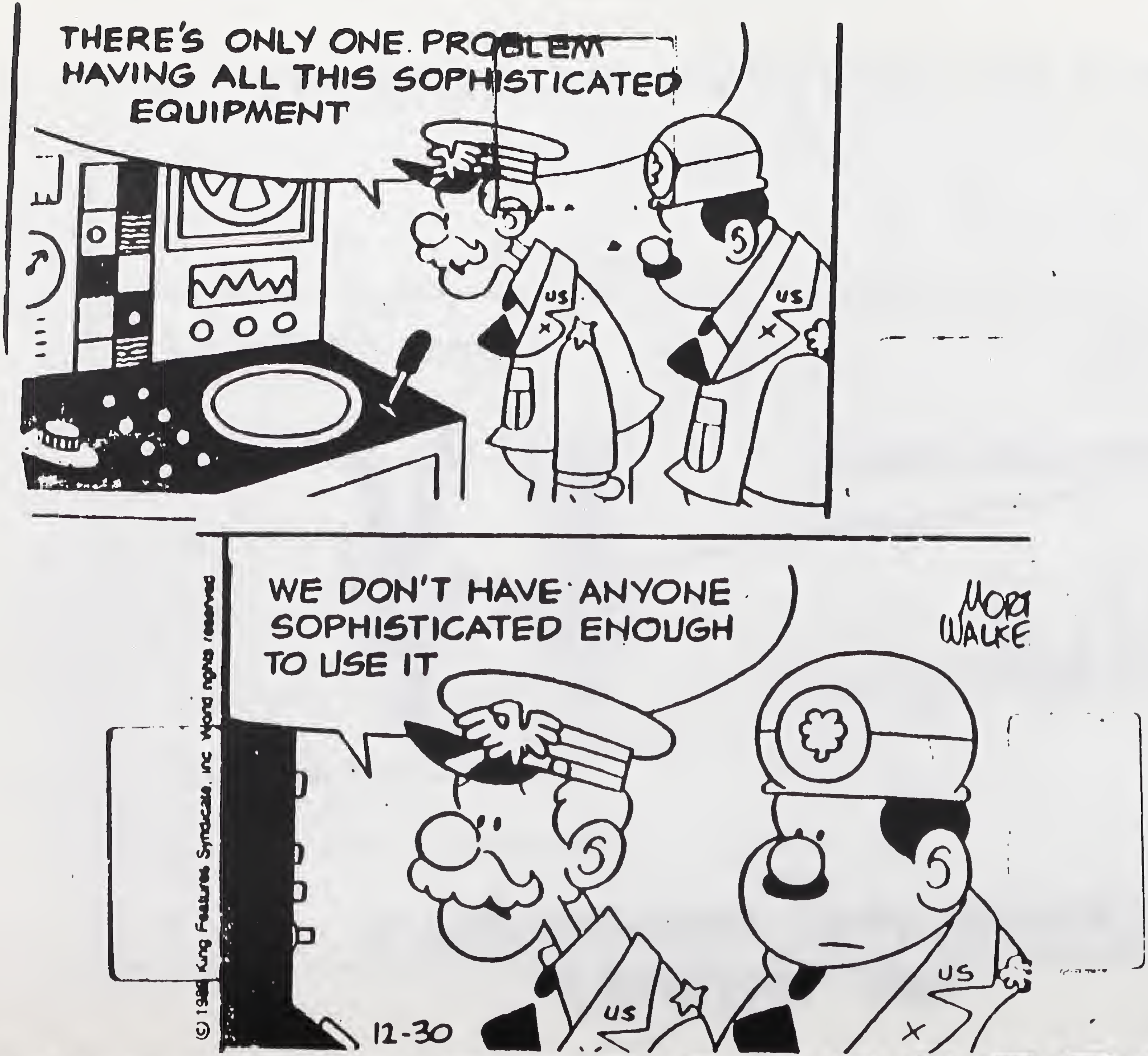

JURISD)NAL CONTROL
STATES
23%
FEDERAL 6%
9,000
nits
CAL (Counties, Municipalities
and Townships)
71%

FEDERAL-AID SYSTEMS MILEAGE

FEDERAL AID SYSTEMS	TOTAL	PERCENT OF TOTAL MILEAGE
Interstate (Arterials)	44,629	1.2
Primary (Arterials)	259,069	6.7
Urban (Arterials & Collectors)	147,035	3.8
Secondary (Collectors)	400,081	10.3
Total Federal Aid Systems	850,814	22.0
Not On Federal Aid Systems	3,020,329	78.0*
Total	3,871,143	100.0

FEDERAL AID
A Partnership That Works!!




THERE'S ONLY ONE PROBLEM HAVING ALL THIS SOPHISTICATED EQUIPMENT
WE DON'T HAVE ANYONE SOPHISTICATED ENOUGH TO USE IT
MORT WALKER
12-30
US
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I. National Service Center (Niessner)

II. Decision Analysis in Transportation (Oskard)

III. Energy and Conservation Related Technology (Ormsby)

IV. High Performance Materials (Pasko)

V. Self-Monitoring Systems (Mc[illegible])

VI. Robots/Automation/Man-Mac[illegible] Woo)

VII. Computer Driven Technologies (Wentworth)

VI. Robots nation/Man-Machine (Woo)

Production

Construction

Maintenance

Continuous Quality C

Hazardous Environme

JOINT HIGHWAY RESEARCH PROJECT

Final Report

FHWA/IN/JHRP-92/13

THE USE OF ADVANCED TECHNOLOGIES IN INDIANA DEPARTMENT OF TRANSPORTATION

Thomas R. Kruse
Kumares C. Sinha

Table 2.4: Possible Barriers to Advanced Technologies

Barrier:	Percent of Sta Respondinc
High Initial Cost	79%
Lack of Trained Personnel	74%
High Operation and Maintenance Cost	56%
General Resistance Against Change	53%
Uncertainty About Potential Benefits	51%
Uncertainty About the Type of Technologies That Can Be Used	35%
Poor Training and Support Offered By Vendors	21%
If You Wait, Even More Advanced Systems Will Be Available Next Year	19%
Fear of Labor Displacement	12%
Lack of Provisions in Contract Agreements	9%
Unable to Get Funding	2%
Liability Regarding IVHS and Anti-Trust	2%
Managers Overburdened by Rate of Change	2%
Space Shortage for Computer Systems	2%
Necessary to Custom Design and Build with Much Systems Integration Work	2%
No Assigned Development Group	2%

high potential for future application.

Table 2.5: Research and Development Projects, 19[illegible]

Area	Percent of States With Projects
Computerized Design, Analysis and Planning	57%
Database Management and Information Systems	46%
Highway Traffic Operations and Management	43%
Laboratory and Field Data Collection and Analysis	33%
Construction Management and Quality Control	15%
Highway Information Systems and User Communications	11%

Table 2.6: Use of Computer Technology in State DOTs - 1985

Area	Percent of States Using High Technology	Percent of States High Potential Application
Database Management	87%	48%
Computerized Design, Analysis and Planning	83%	76%
Laboratory and Field Data Collection and Analysis	72%	30%
Highway Information Systems and User Communications	67%	39%
Automated Sampling and Quality Control	20%	4%
Artificial Intelligence	0%	2%
Other (Shown Below)		

Office Automation (Florida)
Environmental Protection Modeling (Hawaii)
Analytical Models (e.g. HPMS, HIAP, etc.) (Idaho)
Nondestructive Testing of Bridges and Pavements (Minnesota)
Surveying Data Handling (Minnesota)
Communications and Real Time Traffic Control (Texas)
Traffic Management Systems (Virginia)

CREATE "PULL" FOR TECHNOLOGY

THE U.S. GOV'T:

OWNS:	230,000 MILES OF HWY. (6%)
PROVIDES FED AID TO:	600,000 MILES OF HWY. (16%)
SUPPORTS:	270,000 BRIDGES ON FED AID (47%)
MAINTAINS:	2800 MILES OF RAILROAD
OWNS:	417,000 BUILDINGS
LEASES:	68,000 LOCATIONS
ADMINISTERS:	622M ACRES OF LAND (30%)
MAINTAINS:	300M SQ. FT. OF LOW SLOPE ROOFS (ARMY)
BUILDS ~~& CONTROLS~~:	PRISONS, POST OFFICES, MILITARY INSTALLATIONS AND AIRFIELDS, VETERANS HOSPITALS, COASTAL/HYDRAULIC INSTALLATIONS, ETC.

SECTION: 10

2ND WORKSHOP REPORT: TECHNICAL STATE OF THE ART

WORKSHOP PROCEEDINGS

"Application of Robotics and Automation to Highway Construction, Maintenance and Operations"

Proceedings from Day 1 of
"Research Needs in Automated Excavation and Material Handling in the Field"
Workshop

Sponsored by: NSF, NIST & FHWA

April 28, 1993

Courtyard Marriott
805 Russell Avenue
Gaithersburg, MD 20879

TABLE OF CONTENTS

Executive Summary

Why the Workshop?

The purpose of the workshop was to attract selected researchers and practitioners from academia, government and industry to exchange information, ideas and their vision on how "Automated Construction and Excavation" can benefit Civil Infrastructure Systems (CIS).

The size and quality of the world competition in the area of surface and underground construction and excavation technologies dictated an immediate plan of action. The workshop offered the opportunity to professionals of different background to interact with each other, be exposed to different philosophies, and contribute in identifying a coherent set of recommendations for research that will produce the highest returns.

Objectives of the Workshop

The general theme of the meeting was "Automation in Construction and Excavation Technology" with the following **objectives**:

- Present an inventory of state-of-the-art procedures in construction and excavation technologies
- Identify application areas where these technologies will have an immediate return (Transportation, Environmental Protection, Utility Networks, and others)
- Produce a set of recommendations for research needs and identify potential near and long-term programs.

Organization of the Workshop

The NSF, NIST and FHWA sponsors felt that this is the time to obtain a holistic view of the challenges facing the construction and excavation industry. In today's stringent safety and performance requirements there is a need to address the construction and excavation problem from a global perspective. The common theme bonding all the contributors to this workshop was "Automation and Machine Intelligence in Surface and Underground Construction."

The broad range of automated construction /excavation machines includes:

- the automated earth-moving, spreading, compacting machines, and Whittaker's family of autonomous machines at one end of the spectrum
- the continuous mining machines in coal mines,
- the continuous Tunnel Boring Machines in hard rock and weak soils,
- the drill and blast machines, and
- microtunneling machines at the other end of spectrum.

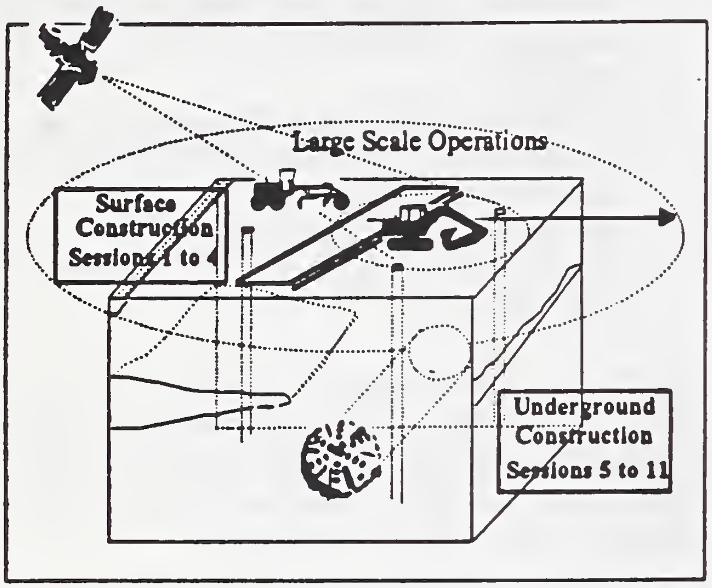
All of these machines are "semiautonomous" with shared man-machine control, operating in a highly unstructured environment. Automation is the common link between all these machines, which although different in size and function encompass:

1. The automatic movement (guided motion) of the machine
2. The automatic manipulation of appropriate tools for the realization of predetermined tasks
3. The automatic sensing and processing of real-time data for decision making and control at the local scale
4. The automatic characterization (detection) of the operating environment at the global scale (macroscale).

The selected topics for discussion covered, in twelve technical sessions, a broad spectrum of application areas, from the highly automated excavation devices at the surface of the soil medium, to the sophisticated TBM's (Tunnel Boring Machines), the continuous mining machines used in the coal mining industry and the different small diameter boring machines used in trenchless technology.

Content of Technical Sessions

The technical areas covered in each session are illustrated below:



In Sessions 1 to 4 the focus was on areas of automation as applied to highway construction and surface operations, while in sessions 5 to 11 the emphasis was on underground excavation and operations related to the development of the underground space. The topics discussed in each session are described below:

Session 1 (Chaired by Arthur Sanderson) focused on the design for automation in highway construction, site integration through hierarchical control, and, automated project planning and scheduling. Road construction and maintenance require extensive coordination of workers, machines, and resources. The use of advanced computer and automation technologies provide the means to improve the efficiency, productivity, and safety of construction projects.

Session 2 (Chaired by Kerien Fitzpatrick) placed the emphasis on technologies for automated earth-moving, spreading, compacting, lifting and positioning of materials and structural elements. Computers and communications technology have revolutionized earth-moving industries. The major changes are still to come, but they are just around the corner. These new developments include basic communication, machine monitoring and diagnostics, job and business management, planning and operations.

In **Session 3 (Chaired by Leonhard Bernold)** presentations were made on teleoperated devices, smart tools, operator-assisted automation, advanced operator interfaces, and virtual reality. The creation of intelligent controls for large and heavy machines used in the construction of highways poses a considerable challenge to engineers and scientists. For example, the unstructured nature of soil in its natural setting requires a thorough understanding of soil mechanics to develop dynamic control systems for robotic excavation. Problems that originate from site conditions in which construction operations have to take place need urgently to be solved.

Session 4 (Chaired by Avi Kak) dealt with technologies for inspection of bridges and road surfaces, automated surveying, "As-Built" databases, site positioning and quality assurance. The focuses of ongoing research activities are on nondestructive testing of highway and runway pavements, and the application of this technology to real time sensing of the quality control of repairs or new construction.

Session 5 (Chaired by William Whittaker) discussed elements of automated excavation, hazardous waste applications, military applications, academic and corporate research. Advances in perception, reasoning and manipulation that have it technically feasible for a robot to discern objects, discriminate them from their surroundings, plan approach trajectories and grasp them. However, an important class of material handling problems related to the extrication of objects that are embedded in soils need to be solved.

In **Session 6 (Chaired by Priscilla Nelson)** new TBM technologies were presented, along with technologies for steering and control systems, perception sensors, automatic lining. New developments in TBM's design include: main beam steering, floating grippers, direct drive cutterheads, mechanical cutterhead stabilization, hydraulic clutch engagement, oil sealing system for cutterhead drive, effective ventilation and dust control, field replaceable cutter assemblies, new safety features.

Session 7 (Chaired by Ken Stokoe) focused on geophysical methods for subsurface detection, site characterization and, subsurface utility engineering. New developments in fusing certified three-dimensional data of soil conditions and underground existing utilities into the field operator console of "smart" equipment. This would guide automated directional excavating machines to avoid existing underground structures. However, presently geophysical exploration is still relying on old technologies that do not use the recent developments in automation.

Session 8 (Chaired by Ray Sterling) elaborated on today's problems and opportunities in R&D for excavation by blasting. Conventional drill and blast, while being able to excavate the hardest of rocks at acceptable efficiencies, are limited in that the technique must be applied in cyclic fashion, resulting in the inefficient and often interfering use of the equipment required for each cycle. Newly developed technologies are shown to be energy efficient for breaking hard rocks and permit more continuous and automated operation.

Session 9 (Chaired by Tom Iseley) dealt with the tracing and steering of horizontal earth boring systems, recent microtunneling innovations and applications of trenchless technology. Trenchless technology is the process of installing or rehabilitating underground infrastructure with minimum disruption and destruction typically associated with traditional methods. There are many methods that make up the family of techniques that can be used to install new infrastructure system.

Session 10 (Chaired by Basile Dendrou) provided the framework in which most of the new technologies introduced in the previous sections was put together in an integrated computer based environment to support the implementation of Mega excavation projects. These technologies included: an automated engineering information system, a reactive navigation scheme, real-time position measurement in underground construction, robotic perception of material properties, dynamic interface simulation for underground construction operations. It is believed that the most efficient way to handle the mega-scale problem of underground excavation projects is with the use of integrated computer platform that will assist in the management and control of automation as applied to the excavation process. The new integrated systems expand on the GIS technology to include the 3rd (depth) dimension, time, and the interaction of all processes characterizing the underground excavation.

Session 11 (Chaired by Herbert Einstein) continued the general theme of the previous session, with more details on the information technology as applied to construction, mechanistic simulations for safety analyses, data fusion and visual data bases, intelligent information systems. Information technology is the natural link between different activities of tunneling construction that includes management-costing programs, and safety and risk analyses.

Finally in **Session 12 (Chaired by Mike Gaus)** the impact of the new excavation technologies on the construction industry was presented through different evolutionary and visionary implementations. Two new ideas were promoted in this session, the concept of underground freight network and the concept of underground urban corridors.

Professionals Attending the Workshop

With the large variety of topics covered in each session it was only natural to have a broad range of professionals of different background participating in this workshop. It was very interesting to see: mechanical engineers interacting with civil engineers, specialists in robotics talking to specialists in geomechanics, construction specialists discussing with manufacturers, and engineers from the military sharing their experience with the private sector. A glance at these new concepts and ideas resulting from these discussions is given in the following sections.

Development Trends Identified at the Workshop

Progress in surface and underground "Automation" technology is necessary if the construction, mining and environmental protection industries are to remain competitive in the world market. The workshop, clearly demonstrated that recent advances in automation technologies, particularly the development of fast, inexpensive computers, control software design, and sensing technology, improve **construction efficiency and worker health and safety**.

In the construction site of the very near future, construction workers and operators will be relocated from the relative dangerous construction site, to a protected Control Center from which the operators will be able to direct the activities of their machines through graphic/video real-time computer terminals. The new technologies for computer-assisted construction are being developed by building upon conventional, mechanized equipment used in well-understood construction operations. By using familiar machines in familiar ways, the manufacturers hope to avoid confronting the barriers traditionally associated with introducing radically new machines and procedures. This trend was clearly identified in many sessions of the workshop dealing with different excavation machines. Table 1 shows typical machines and their "automation" components, as identified at the workshop.

Benefits of the Automated Construction and Excavation

The potential benefits of "Automation" in excavation technologies include: quicker and higher quality site characterization, improved craftspeople performance, improved modular construction, reduced rework, improved performance and quality improvement, and improved overall construction time.

The benefits according to preliminary estimates given by Dr. Yvan Beliveau can be **more than $150 billion per year in savings from the $500 billion U.S. Construction industries.** Most of these spendings are planned for construction at the surface. However, the underground space may well be the new frontier for the U.S. construction industry.

The underground excavation industry offers a unique opportunity to attract the interests of many different professions and put into practice new technological concepts and ideas, as shown in the closing session of the workshop. Potential new surface and underground developments for the next 5 years in the U.S. alone include:

In Surface Transportation:

- $5-$10 billion dollars for the rehabilitation of highways
- $20 billion dollars for expanding the highway network

Candidates for the implementation of these projects are: Surface excavators.

In Underground Transportation:

- $6-8 billion dollars for new programs in urban railway transportation
- $2 billion dollars for new highway tunnels
- $10 billion dollars during first 5 years and increasingly thereafter for the new underground freight systems

Candidates for the implementation of these projects are: TBM's, Drilling Machines.

In Mining:

- $2 billion dollars for new Mines
- $20 billion per year for ongoing operations

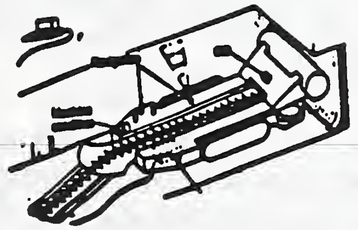
Candidates for the implementation of these projects are: Mining Machines, Drilling Machines, Surface Excavators.

In Water Management:

- $5 billion dollars for rehabilitating existing pipe networks
- $6 billion dollars for new construction of water facilities
- $4 billion dollars for new sewerage networks

Candidates for the implementation of these projects are: TBM's, Trenchless technology, and surface excavators.

Table 1 Typical Automated Machines

Machine Type	Features and Functions
Surface Excavators 	Semi-autonomous machines operator assisted. Real-time Positioning: GPS, (2" accuracy) Automotive: compt. enhanced automotive fcts. Electronic Hardware: RISC +LAN's technology Software: Assembly and C on RO chips. US against Foreign Competition: Ahead
Whittaker's Family of Machines (Primarely for material handling in the field) 	Remote-supervised operating system (semi-autonomous) and automous machines Real-time Positioning: LPS (0.2" accuracy) Automotive: Traditional (Battery) Electronic Hardware: RISC Software: Assembly US against Foreign Competition: Ahead
Mining Machines 	Computer-assisted, remote-supervised operating system (semi-autonomous) Real-time Positioning: LPS (Laser Based) Automotive: Electric Power Electronic Hardware: RISC - CISC Software: Assembly and C, Video Console US against Foreign Competition: Ahead
TBM (Tunnel Boring Machine) 	Computer-assisted, manually remote-supervised operating system (semi-autonomous) Real-time Positioning: LPS (Laser Based) Automotive: Traditional Gas /Electric Software: Conventional, Video Console US against Foreign Competition: Weak
Drilling and bolting machines 	Automated mechanically-assisted operation. (semi-autonomous) Real-time Positioning: LPS (Laser Based) Automotive: Traditional Gas Electronic Hardware Traditional Software: Assmbly and C US against Foreign Competition: Even
Trenchless Technology 	Remote-supervised operating system (semi-autonomous) Real-time Positioning: LPS (Laser Based) Automotive: Traditional Electronic Hardware State of the Art RISC Software: Assembly and C, Video Console US against Foreign Competition: Weak

In Clean up Operations: (Information provided by Dr. Vernon Myers)

- $50 billion for 2000 Superfund sites
- $100 billion for 3,750 RCRA sites
- $10-$15 billion for 6,000 sites of DOD
- $53-90 billion for 45 sites of DOE
- $100 billion for 30,000 Real Estate sites

Sixty percent of these cleanup operations require the use of excavation technologies. Candidates for the implementation of these projects are: TBM's, Trenchless technology, and surface excavators.

Underground utilities:

- $0.5-1 billion dollars for communication networks
- $1 billion dollars to create underground space in major cities

Candidates for the implementation of these projects are: TBM's, Trenchless technology. The 1992 World Market for trenchless pipelaying is estimated at approximately $4.7 Billion (Kramer,1993)

These are only conservative estimates but the important fact is that the magnitude of these new financial ventures is such that "Automated excavation" can make a significant contribution towards the infrastructure investments that are necessary to help reverse the recent downward trend of the U.S. economy.

Promoting and Expanding "Automated Excavation Technology"

Technology alone is not enough to commit the governmental agencies and the investors to these new developments. The discussions at the workshop clearly indicated that there is a need to attract the popular concern as represented through the legislative institutions and regulations. According to attorney David Calverley, environmental regulations in the area of the utilization of underground space, are not nearly as well developed as in other media. An integrated regulatory scheme could significantly assist in the overall growth of the industry, while assuring at the same time, that the goals of sustainable development are met.

However, the single biggest issue to the overall success of these technologies is to properly educate, retrain, attract, and retain well-qualified professionals of the technology. It was the consensus of all the participants that the level of resources that the construction industry spends for training and education is inadequate (1% of its sales compared to 10% of sales for manufacturing). To remedy this, the participants of the workshop agreed to follow the Dr. Herbert Einstein's advice and create a "virtual network" of dedicated professionals that will actively support the promotion of "Automated Excavation Technology."

There are undoubtedly costs associated with the implementation of these technologies. **In the final analysis, however, it is expected that each dollar of added effort will yield tenfold and even larger returns.**

Technical Challenges

The new developments in automated surface and underground excavation include:
1/ the identification of in situ conditions using the latest technology in sensor devices (geophysical site investigation), 2/ Processing the in situ information through computers and expert modules to establish design and construction strategies, 3/ Adapt automatically the excavation tools and proceed with the excavation, 4/ Remove and automatically process the excavated material, 5/ Install automatically the lining or other structural system, and 6/ Complete the job to satisfy building code's safety requirements.

To implement all these tasks a broad range of different technologies must be blended together in a macroengineering framework (macro-scale approach).

The challenge now is to integrate these technologies in the "semiautonomous" excavation machines, operating in the highly unstructured environment of the real world. The following table provides a summary of the different disciplines required for the "Automation" of most of these excavation machines.

Automated Function	Disciplines & Technologies
Automatic movement (guided motion) of the machine.	**Robotics:** Robotic control and mobility, Task planning, Intelligent sensors and actuators, Automatic drilling and lining systems. **Manufacturing Automation:** Flexible manufacturing, Process automation, Computer integrated manufacturing.
Automatic manipulation of appropriate tools for the realization of predetermined tasks	**Control Applications:** Motion control, Guiding systems, Modeling and simulation, Signal processing, Fuzzy control and diagnosis.
Automatic sensing and processing of real-time data for decision making and control at the local scale	**AI & Expert Systems:** Knowledge bank. Intelligent control, AI software. Network dynamics, learning algorithms, hardware implementation **Global and Local Positioning:** Laser network. Infrared technologies. **Computer Vision:** Image processing, Dynamic scene analysis, Machine vision, Pattern recognition. Fractals and IFS algorithms.
Automatic characterization and detection of the operating environment at the global scale (macroscale). Automatic Stabilizing counter measures.	**Site Characterization and Detection:** Geophysical methods, Real time sensors of evolution of mechanistic processes. **Mechanistic and Construction Simulation:** Prototyping, Parallel processing, Impact of automation to the environment, Reliability and risk analysis, Management and cost. **Soil/Rock Stabilization:** Concrete admixtures, Geotextiles, Fiber anchors, Chemicals for soil grouting and stabilization.

The overall research, development, demonstration program should be on a 5 year schedule requiring a total funding of $15 to 20 million dollars for a target machine system. TBM's and mining machines will require more research funds than microtunneling and material handling machines.

Automated Function	R & D Cost Estimate
Automatic movement (guided motion) of the machine.	**Robotics:** $4 million **Manufacturing Automation:** $2 million
Automatic manipulation of appropriate tools for the realization of predetermined tasks	**Control Applications:** $4 million
Automatic sensing and processing of real-time data for decision making and control at the local scale	**AI & Expert Systems:** $1 million **Global and Local Positioning:** $1 million **Computer Vision:** $1 million
Automatic characterization and detection of the operating environment at the global scale (macroscale). Automatic Stabilizing counter measures.	**Site Characterization and Detection:** $ 4 million **Mechanistic and Construction Simulation:** $1 million **Soil/Rock Sciences:** $ 2 million

These key technologies can be tested in certain important critical missions, such as:

- The cleanup operation of the nuclear power plants.
- Other major government excavation projects.

National Geotechnical Experimentation Sites (NGES) sponsored by NSF and FHWA would provide the means of field-testing these technologies in the development stages.

Recommendations

Here are some key suggestions for what the research community and funding agencies, might realistically do to foster more effective research in the area of "Automated Excavation and Material Handling in the Field":

- There are four areas for "Automation" that are intimately interrelated and thus require a mechanism where sharing of ideas can take place. Small workshops need to be held to discuss how to encourage multi-investigator proposals.
- The methodology for research and development in this area needs to move out from the confines of the laboratory and into real-life contexts. The field of "Automated excavation" is in an exploratory phase right now; in situ style studies must be encouraged.
- The development of underground space with its multitude of application areas represents a multibillion dollar market requiring the use of automated excavation tools that are still at a prototype stage. More than 100 million dollars are probably needed to complete ongoing research, requiring the active participation of the private sector. Federal Agencies need to interact with each other and identify needed incentives to attract private US and foreign investors.
- Automated excavation technology is an integral part of any environmentally sustainable development. However, there is a need to define the metrics for measuring sustainability in excavation procedures. Macroengineering may be the proper vehicle to quantify sustainability. The creation of a "think tank" to address this problem, is strongly recommended.
- The personnel to adequately handle the size and complexity of the new projects requiring excavation technology is inadequate. The possibility of converting part of the defense industry to fulfill the needs of these major government excavation projects must be closely examined in a future workshop.

Acknowledgments

The organizing committee would like to acknowledge Drs. Mehmet Tumay, Ken Chong, Howard Moraff of the NSF and E. Kent of NIST for initiating and funding this workshop or **"Research Needs in Automated Excavation and Material Handling in the Field."**

We also want to thank Dr. Don Linger of the DNA for his encouragement and moral support.

The success of this workshop would not have been possible without the contribution of all the participants before the meeting. We are thankful to the individuals who volunteered to write position papers and the chairpersons for their writing of the pre-workshop summary reports.Finally, we would like to express our appreciation to NSF/NIST/FHWA for their support.

Companies contributing to this workshop are the following:
The Robbins Company, Caterpillar Inc.
Kraft Telerobotics Inc., Jacobus Technology Inc.
Phoenix Scientific Inc, .Olson Engineering Inc.
So-Deep Inc,.Sunburst Excavation Inc.
MicroEngineering Inc., Horizontal Holes International Inc., Iseki Inc, Ampower Corporation, Transystems Inc., Spectra Physics, Hayward-Baker Inc., TRW , Image Machines Corporation, AMS Reasearch Inc. (KROME Computers).

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Civil Engineering Research Foundation, " Setting a National Agenda for the Civil Engineering Profession", Volume 1, August 1991, report No. 91-F1003.

Session #1

Project-Scale Control and Design

Chaired by:

Arthur Sanderson
Rensselaer Polytechnic Institute

Participants:

Kenneth Goodwin, NIST

Iris Tommelein, University of Michigan

A.B. Cleveland, Jacobus Technology, Inc.

NIST/FHWA WORKSHOP ON
AUTOMATION AND ROBOTICS IN
ROAD CONSTRUCTION, MAINTENANCE,AND OPERATIONS

SESSION ON PROJECT-SCALE CONTROL AND DESIGN

"SESSION OVERVIEW: ISSUES AND APPLICATIONS IN PLANNING, INTEGRATION AND DESIGN"

Arthur C. Sanderson

Road construction and maintenance require extensive coordination of workers, machines, and resources. The use of advanced computer and automation technologies may provide means to improve the efficiency, productivity, and safety of construction projects. Often the sequence or concurrency of operations is critical to success. The complexity of planning and scheduling to best achieve effective materials handling, use of machines, and quality of the project is well-suited to computer-based methods which incorporate interactive optimization and knowledge-bassed planning tools. As more automated and sensor-related operations are developed for use in construction projects, the integration of machines and sensors becomes essential. An 'architecture' which systematically describes the interconnection and communications among machines, sensors, and users makes this integration possible, and may make many new tasks and approaches possible. Design underlies all of the planning and execution of projects, and new computer-aided design tools improve the efficiency of design, but also yield a representation of sites, parts, and structures which encourage better planning,more complete integration, and the possibility of new more efficient methods. 'Design for automation' specifically addresses the development of components and processes which enable new operations and tools. This session will highlight the underlying technologies for planning, integration, and design, and describe examples of current and future use in road construction.

PLANNING, INTEGRATION AND DESIGN FOR ROAD CONSTRUCTION AND OPERATIONS

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Automation and Robotics
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Troy, NY

SESSION OVERVIEW:
PROJECT-SCALE CONTROL AND DESIGN

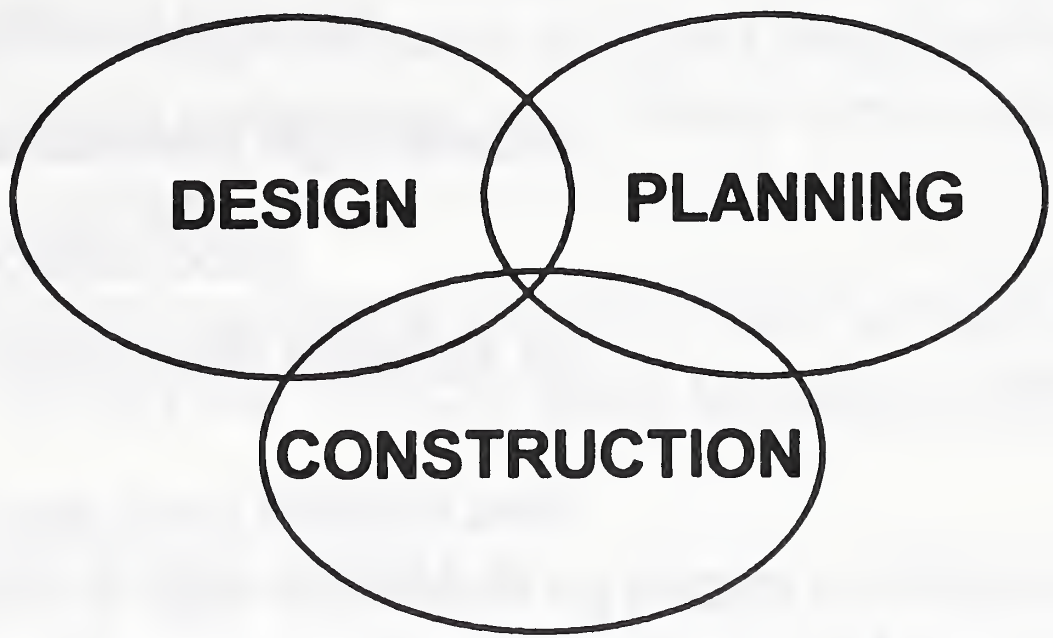
1. A. C. Sanderson - Planning, Integration, and Design for Road Construction and Operations

2. I. D. Tommelein - Site Layout Scheduling for Construction Materials Management

3. J. Albus - Hierarchical Architectures for Site Integration

4. A. B. Cleveland - Design Issues in Construction Planning

CONCURRENT ENGINEERING IN CONSTRUCTION



WHAT IS PLANNING?

Planning is the ordering of tasks to optimize the use of time and resources.

Better planning results in:

- Lower cost
- Improved efficiency
- Higher quality
- Safety

HIERARCHICAL PLANNING

- PROJECT LEVEL

  Sequencing of major project segments, for example: Build retaining wall, Pour concrete roadbed ...

- TASK LEVEL

  Sequencing tasks within major project, for example: Excavate trench, pick up pipe, align pipe ...

- OPERATIONS LEVEL

  Individual operations such as: Move crane to pipe, grasp, move crane to trench, lower pipe, ...

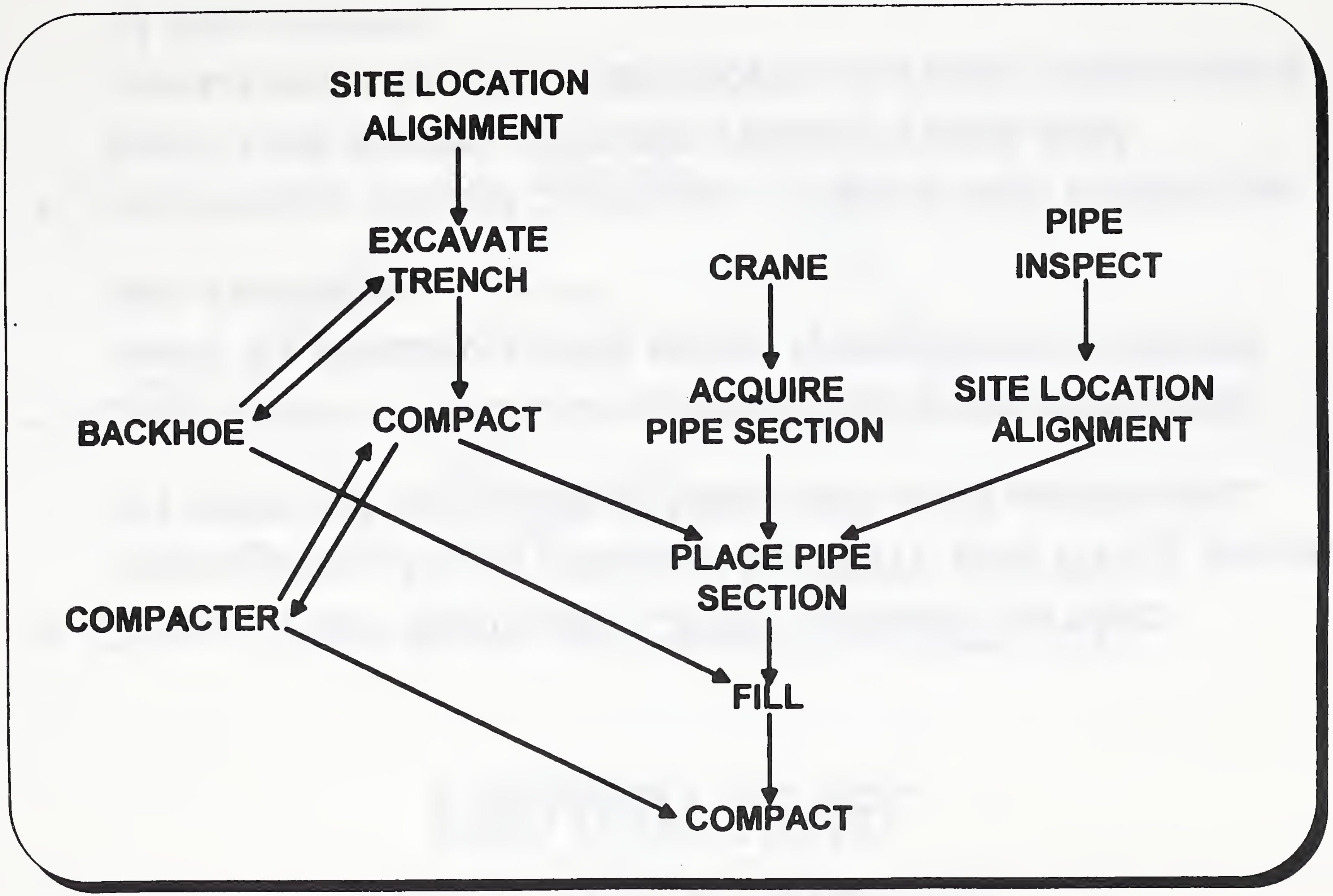
COMPUTER-BASED PLANNING TOOLS

Many of the tools developed for robotics and automation systems can be applied effectively to construction projects.

These tools:

- Capture knowledge of a specific domain, such as road construction
- Efficiently store and retrieve large data sets
- Reason about domain to aid in decisions
- Interact with the user as a computer-based assistant

EXAMPLE OF PLAN - PIPE PLACEMENT



TOOLS FOR PLANNING: PROJECT LEVEL

- Critical Path Methods (CPM) - general project management tool (related to PERT and PPS), based on network analysis of time and cost estimates.
- Optimization Methods - analytical and numerical tools as decision aids when quantitative models are available.
- Knowledge-based Systems - logical and relational tools use stored, domain-related rules and constraints to infer decisions and plan sequences of operations.

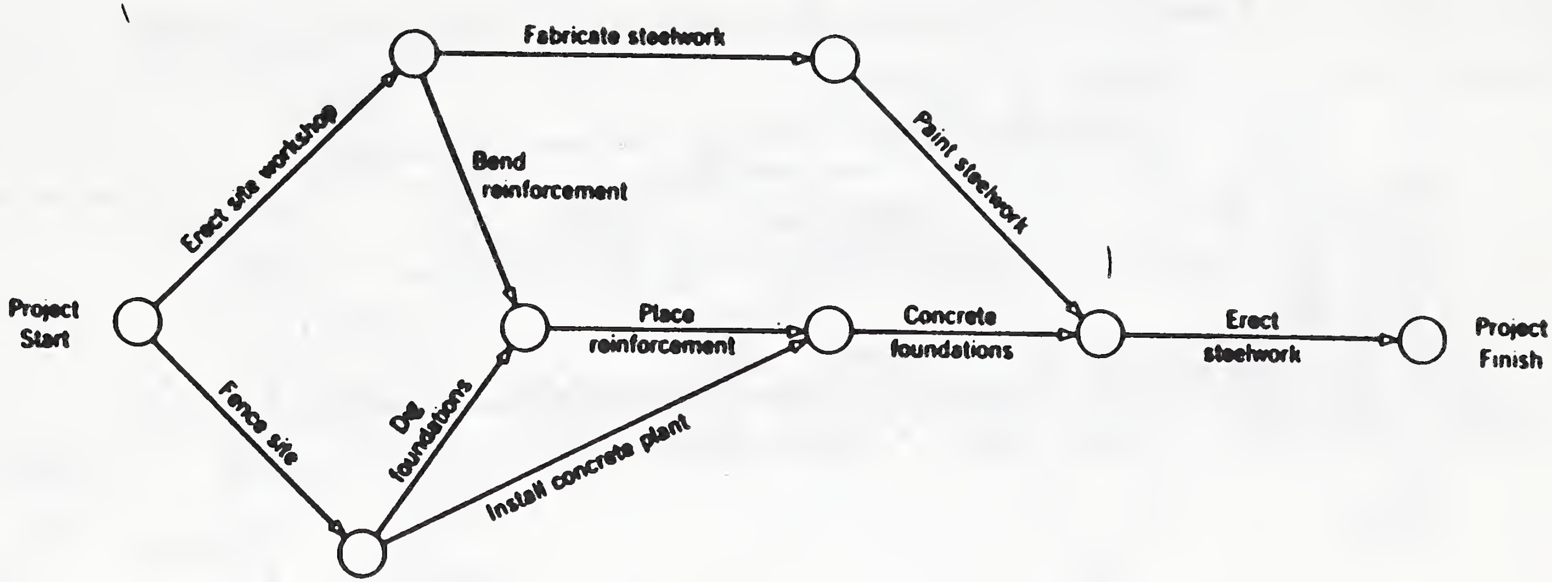


Figure 1.1 Network diagram for a simple project, showing component operations.

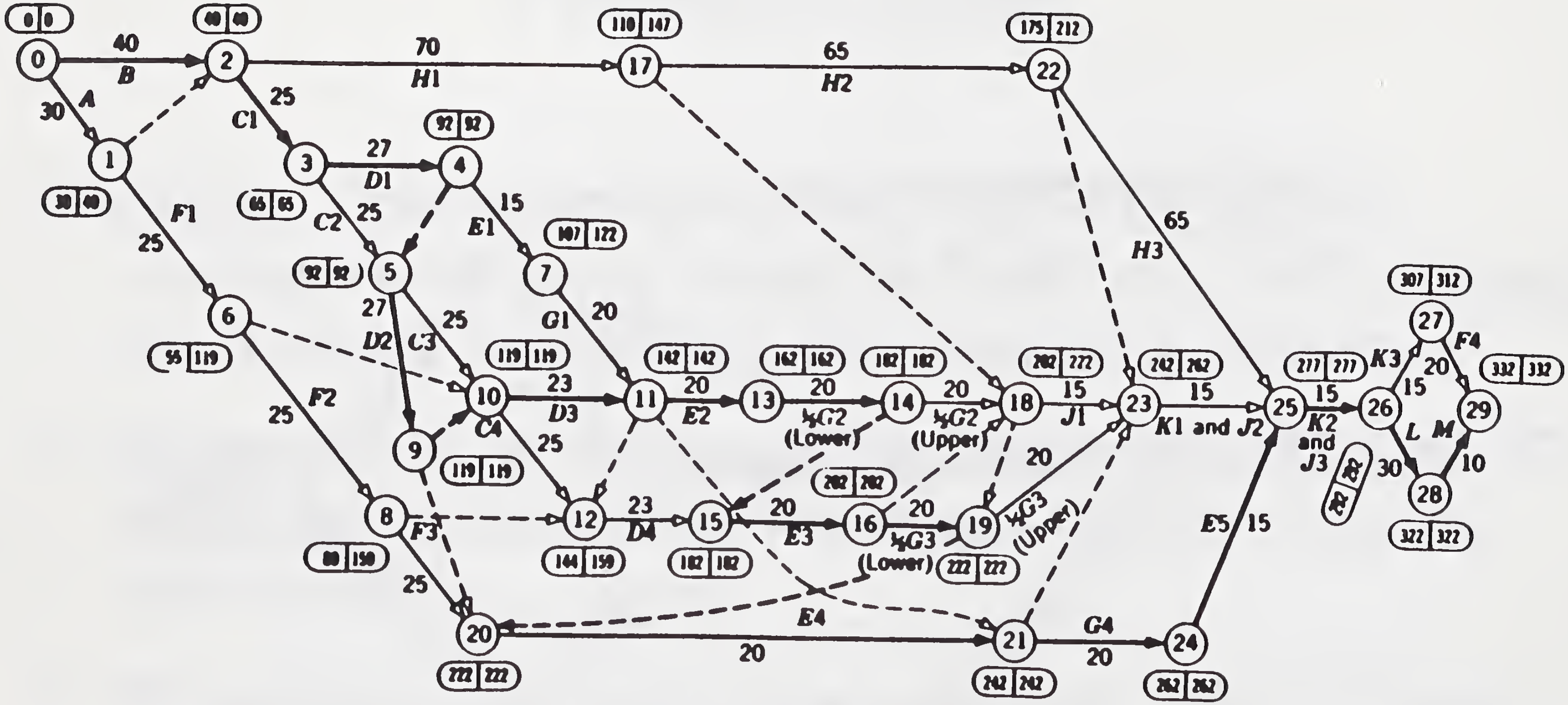


Figure 8.1 First network, three-span bridge (casting piles on site): $T_P = 332$ days.

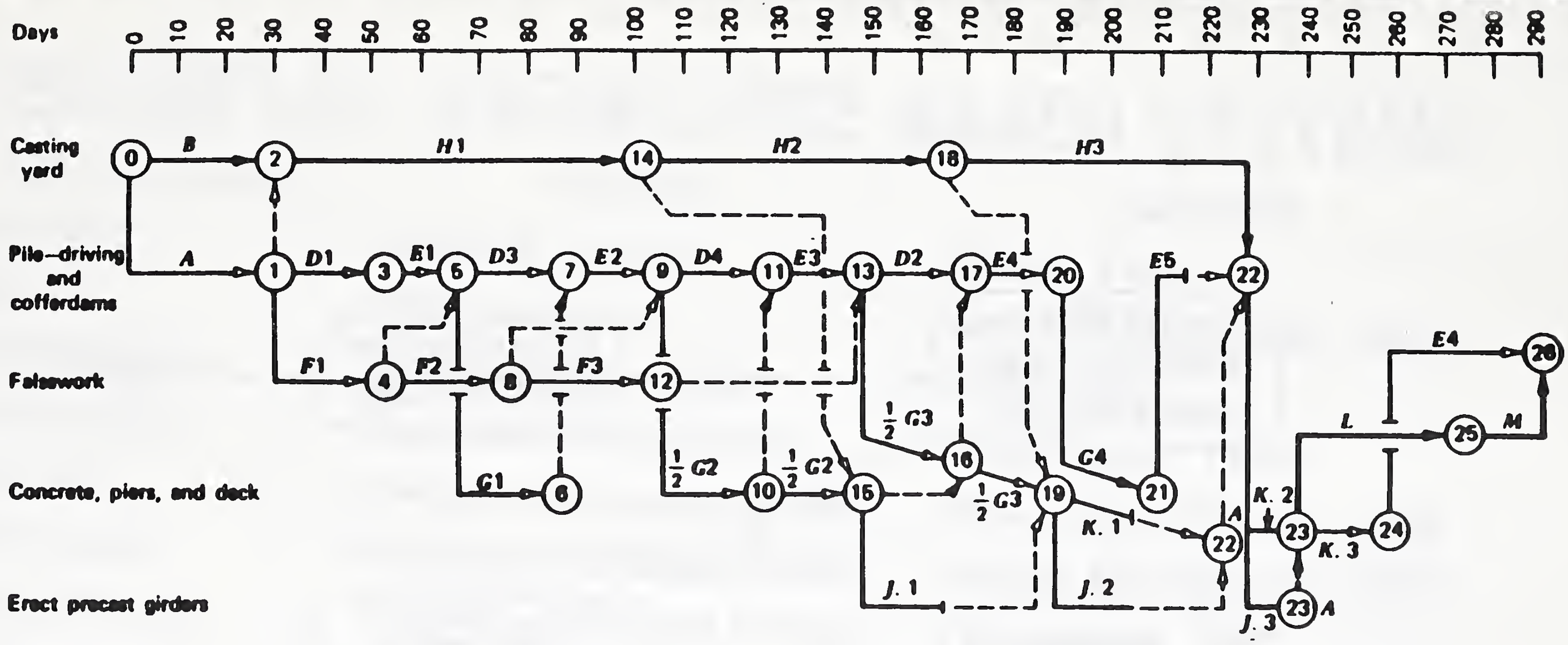
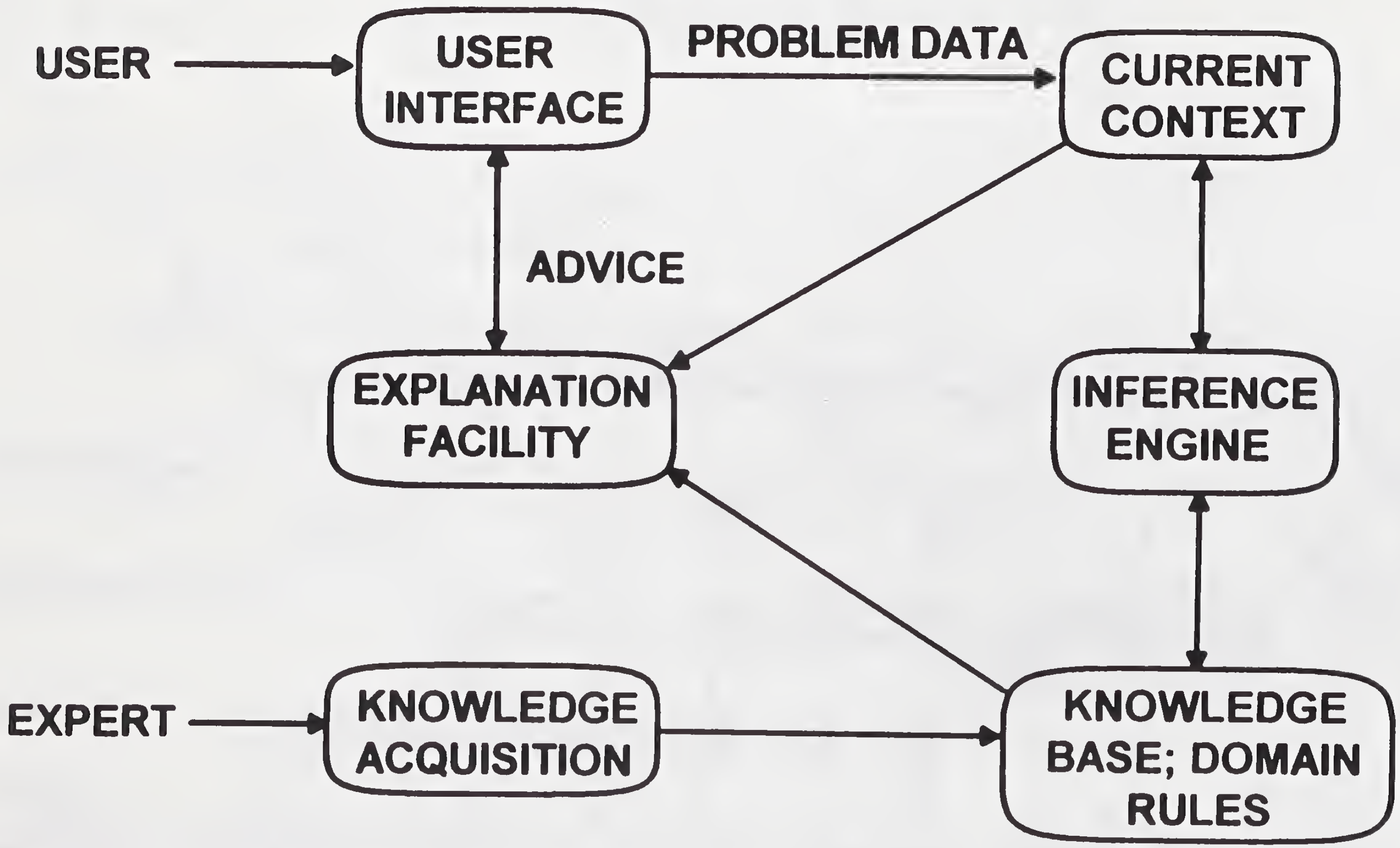


Figure 8.4*b* Final network, three-span bridge (drawn to time-scale) : $T_p = 285$ days.

KNOWLEDGE-BASED SYSTEM



EXAMPLES: KNOWLEDGE-BASED SYSTEMS

SYSTEM NAME	DOMAIN	AUTHOR
HI-RISE	Building design	Maher, 1984
BDES	Bridge design	Welch and Biswas, 1986
BTEXPERT	Bridge truss design	Adeli, 1988
RETWALL	Retaining wall design	Hutchinson, 1985
SPIKE	Design standards check	Rasdorf and Wang, 1986
SOILCON	Soil exploration consult	Ashley and Wharry, 1985
SIGHTPLAN	Construction site layout	Tommelein, 1987
CONSITE	Construction site layout	Hamiani and Popesen,1988
PLANEX	Construction planning	Hendrickson, 1987
HOWSAFE	Safety evaluation	Levitt, 1986
CONSAES	Project scheduling	O'Connor, 1986
KYBAS	Bridge structural analysis	Fenske and Fenske, 1990
ITDS	Traffic Data System	Rathi, 1990
TRANZ	Traffic ctl in work zones	Faghri and Demetsky, 1990
SAFEROAD	Highway safety structures	Roschke, 1991

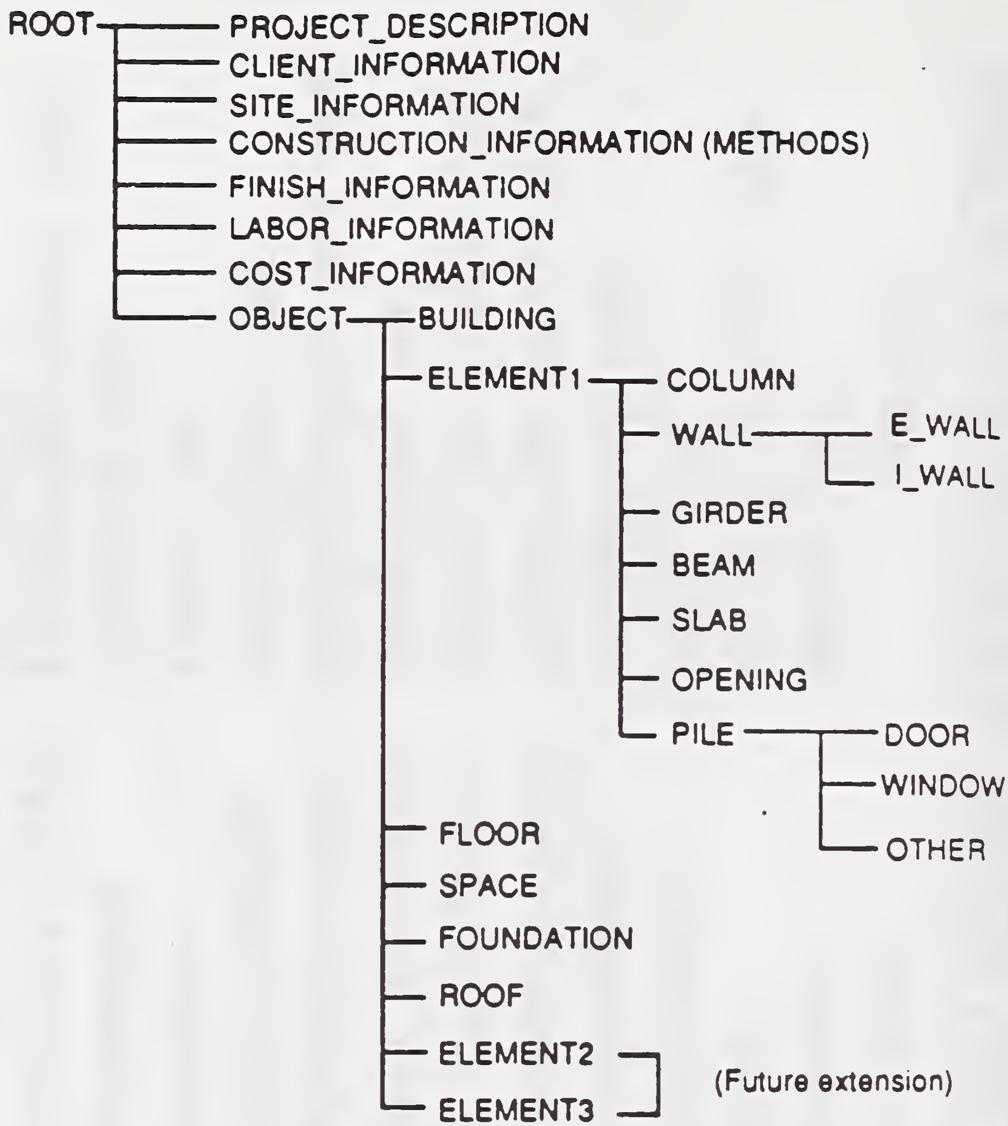


Figure 11-3 Elements of the OARPLAN product model in PMAP (adapted from [Ito 1989]).

- **Component properties**, such as dimensions, material composition, and finish specifications, are provided when OARPLAN accepts default values, which are correct in many cases. As project definition proceeds,

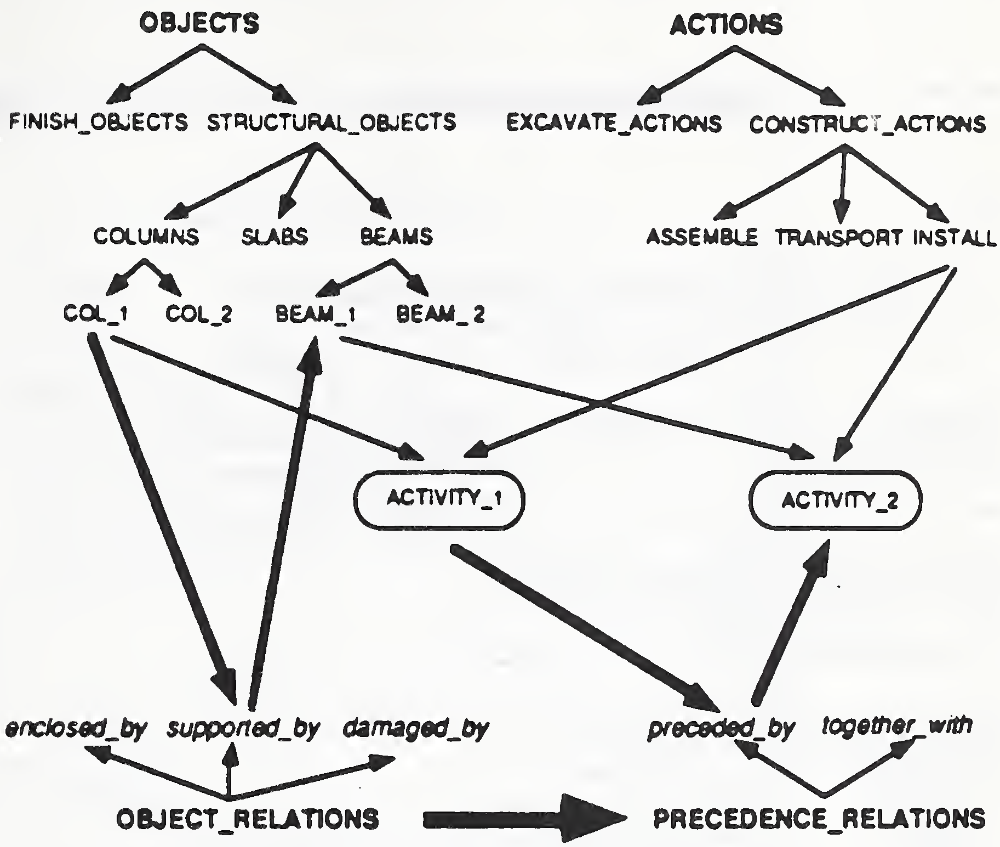


Figure 11-5 Reasoning from object relationships to activity dependency in OARPLAN.

Some specific examples of the dependency rules that the OARPLAN prototype system utilizes to develop plans for low-rise frame buildings are

- **Supports constraint.** Columns must be placed before the beams they support. The relation between the object constituents of the activities for installing columns and installing beams is *supported_by*.

- **Safety constraint.** In steel-framed buildings, do not start work on the members of floor *n* until the slabs of floor *n-1* or floor *n-2* are constructed. The relation here between activity objects is that *they belong to floors that are one or two levels apart.*

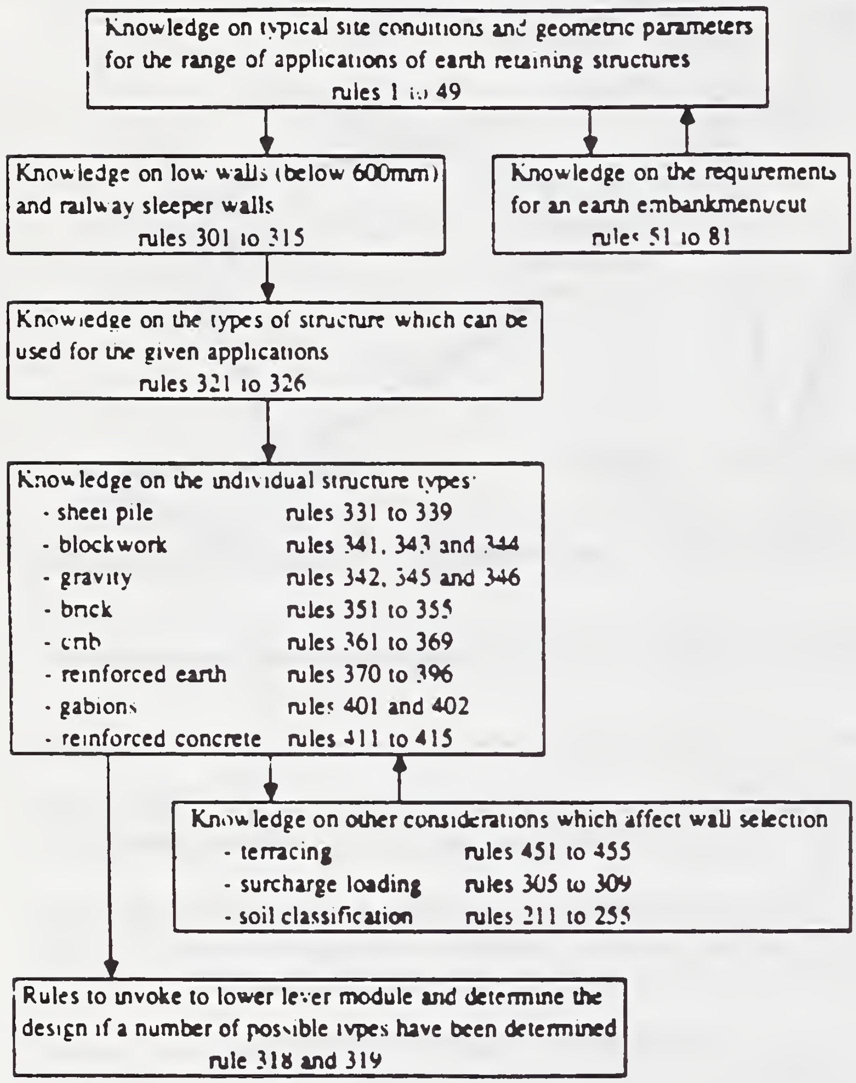
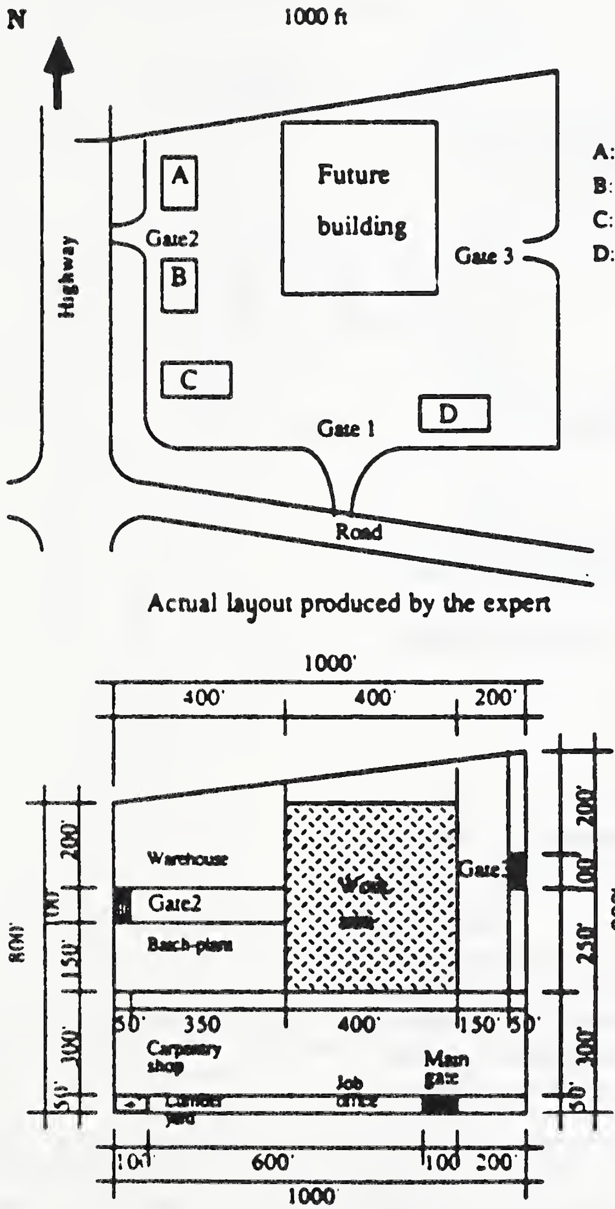


FIGURE 13. Schematic layout of all the knowledge blocks in the higher-level module. (From Hutchinson, P., An Expert System for the Selection of Earth Retaining Structures, M.S. thesis, University of Sydney, Department of Architectural Science, Australia, 1985. With permission.)

embankment or cut could be constructed. If not, then it is determined by default that an earth-retaining structure is required.

The knowledge on the types of structure suitable for a given wall application provides a higher-level control on the search and determines the order in which the various wall types are considered, and which types are considered for every application. If the types considered by these rules prove to be



Final layout produced by CONSITE

FIGURE 9. Output of CONSITE after solving the office-building problem. (From Hamiani, A. and Popescu, C., Proc. 5th ASCE Conf. Computing in Civil Engineering: Microcomputers, Will, K. M., Ed., ASCE, New York, 1988, 248. With permission.)

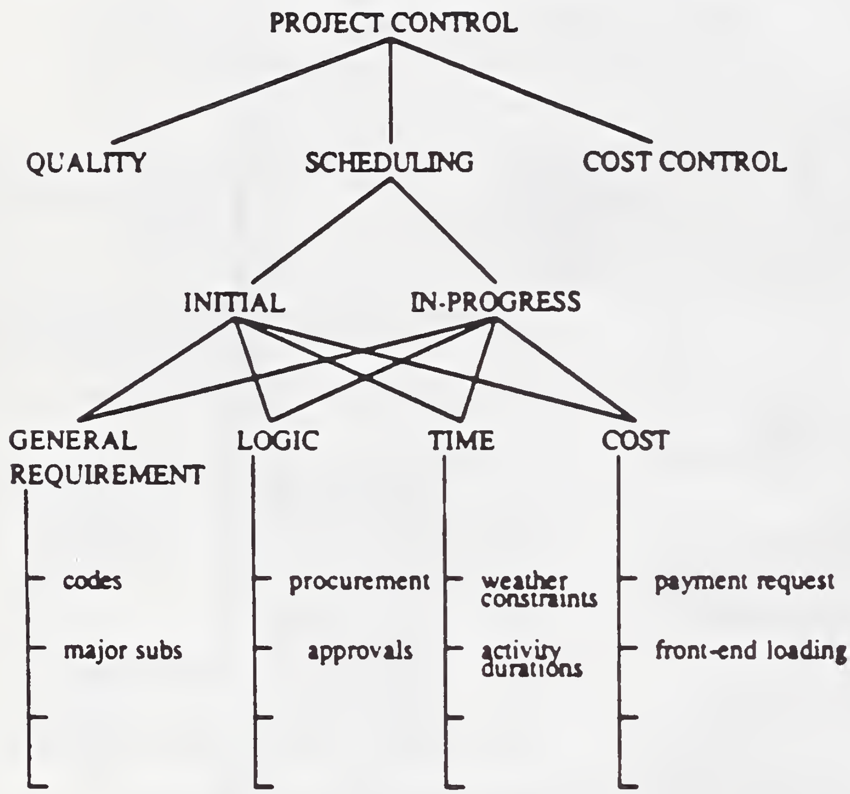


FIGURE 21. Knowledge structure (From O'Connor, M. J., De La Garza, J. M., and Ibbs, C. W., Jr., Proc. ASCE Symp. Expert Systems in Civil Engineering, Kostem, C. N. and Mayer, M. L., Eds., ASCE, Seattle, 1986, 55. With permission.)

type of information that contractors present to owners for verification before the commencement of the project. Typical information would consist of the owner's approval activities, participation of major subcontractors in the formulation of the plan, etc. The in-progress scheduling evaluation module allows project managers to examine questions such as delay and duration modification concerns.

4.3.6.2. Methodology

CONSAES (CONstruction Scheduling Analysis Expert System) relies upon existing project control system software to (1) identify and capture expressions of similar form in the "paper" knowledge base, (2) determine the specific target inference engine, (3) decide how the "paper" knowledge base is to be represented in the inference engine, and (4) develop a mapping technique to adapt the concepts, facts, and rules to the corresponding engine syntax.

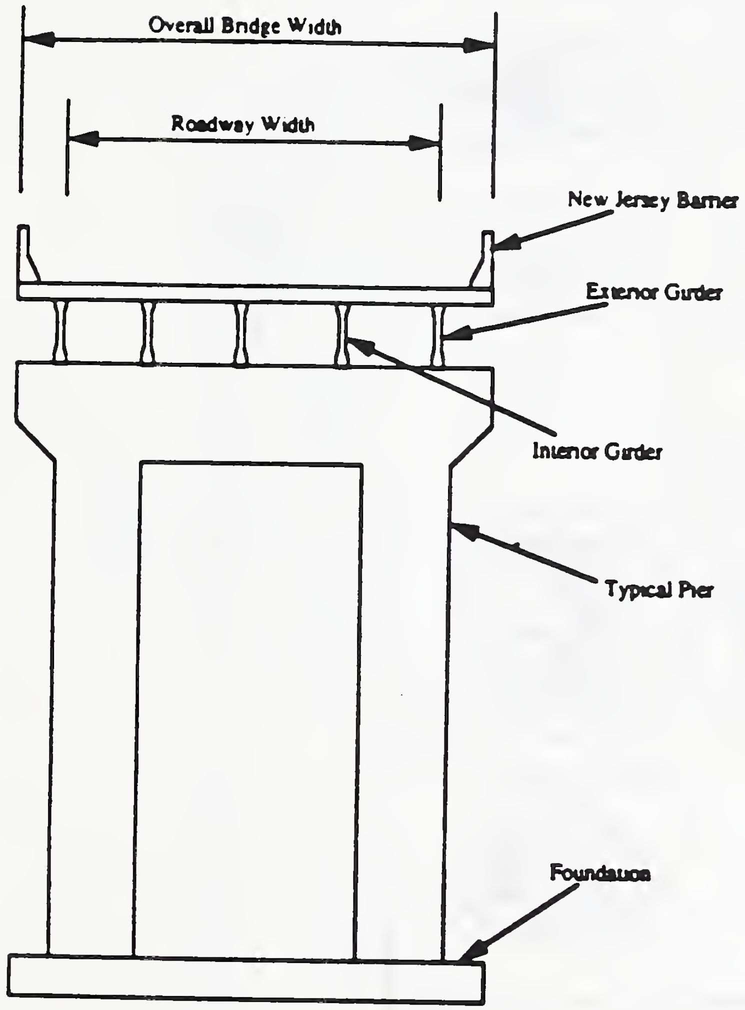


FIGURE 2. Typical bridge configuration recommended by KYBAS. (From Fenske, T. E. and Fenske, S. M., *Developments in Short and Medium Span Bridge Engineering '90*, Toronto, August 1990, 23. With permission.)

AASHTO girder types, diaphragms and their related location in each span, etc. These recommendations are based upon user input to queries regarding clearance, usage, and site location. Figure 2 shows a typical girder bridge configuration recommended by KYBAS.

The prototype RCBD (Reinforced Concrete Bridge Design) ES (Nguyen, 1990) for selecting a reinforced concrete bridge was developed by using the VP-Expert development tool. RCBD is a rule-based ES that has more than 100 rules in its knowledge base. There are 12 different types of bridges for the goal variables and eight dependent variables for the bridge: span length,

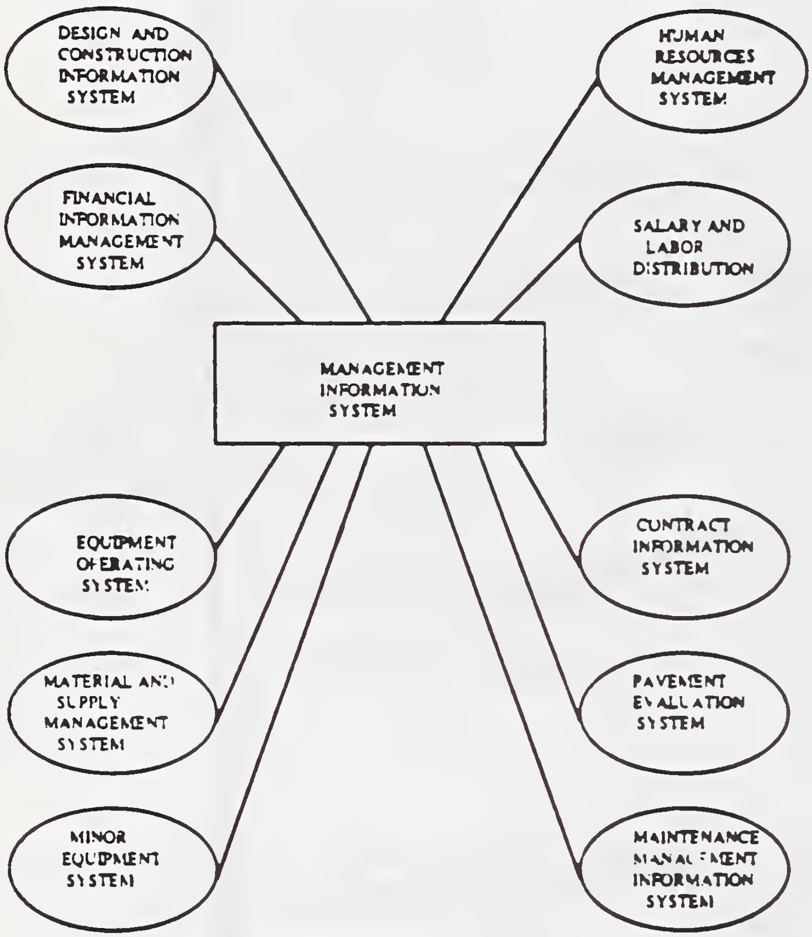


FIGURE 2. Management information system. (From Howell, T. F., *J. Transp. Eng.*, 116(6), 831, 1990. With permission.)

strategies. Transportation engineers can design and evaluate various alternative traffic control strategies prior to their real-life implementation. This evaluation helps reduce motorists' operating costs, vehicular fuel consumption and emissions, and costly retrofits, which occur when a problem is detected only after implementation.

Traffic models, however, have a few major difficulties associated with their use. Basically, there is no consistency in the definition of traffic-related terminology used by different models. Also, since these computer programs were written for use in a batch processing mode, a card image input data file must be prepared for each run. This makes them awkward and time consuming to use. Finally, due to the limitations of these models, users who are devel-

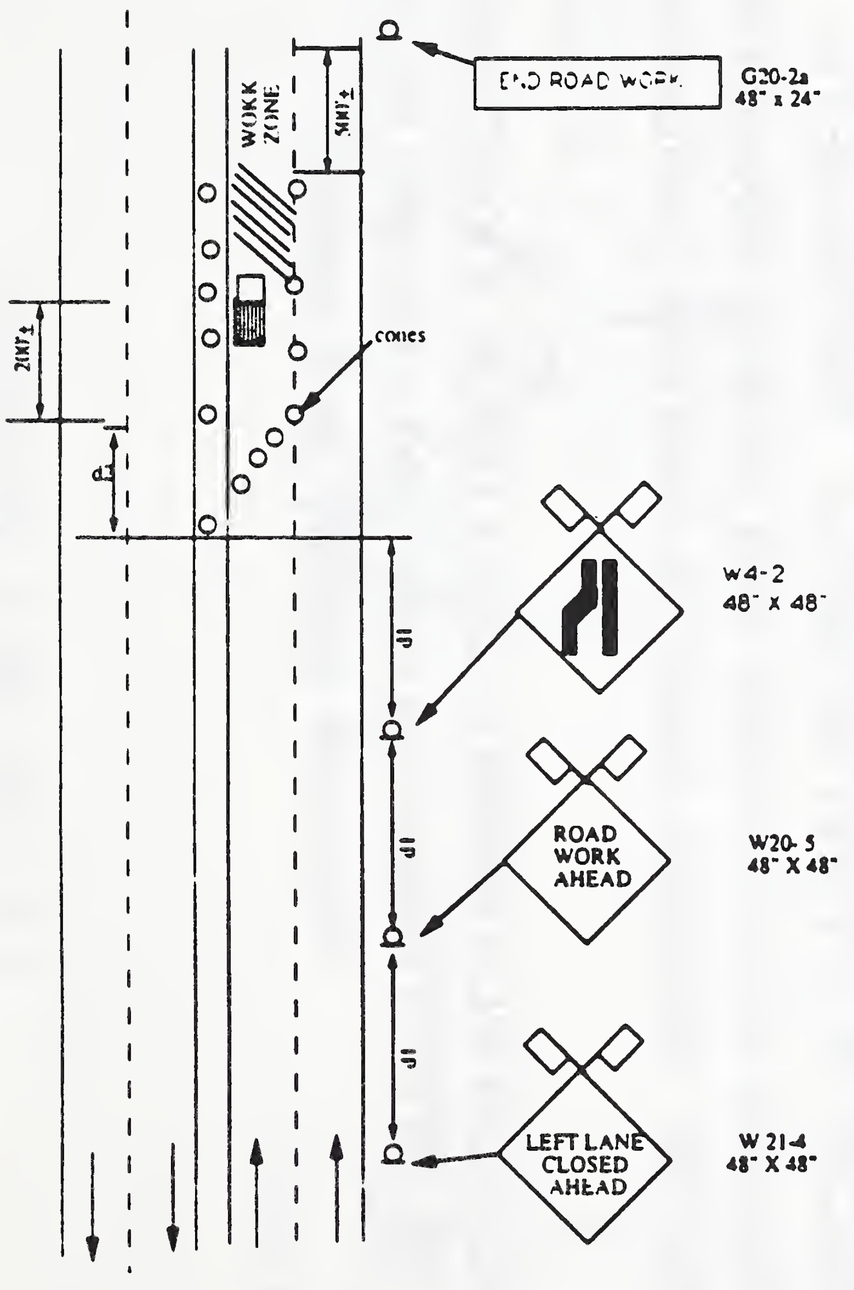


FIGURE 7. Typical maintenance operation on secondary highway. (From Faghri, A. and Demetsky, M. J., *J. Transp. Eng.*, 116(6), 759, 1990. With permission.)

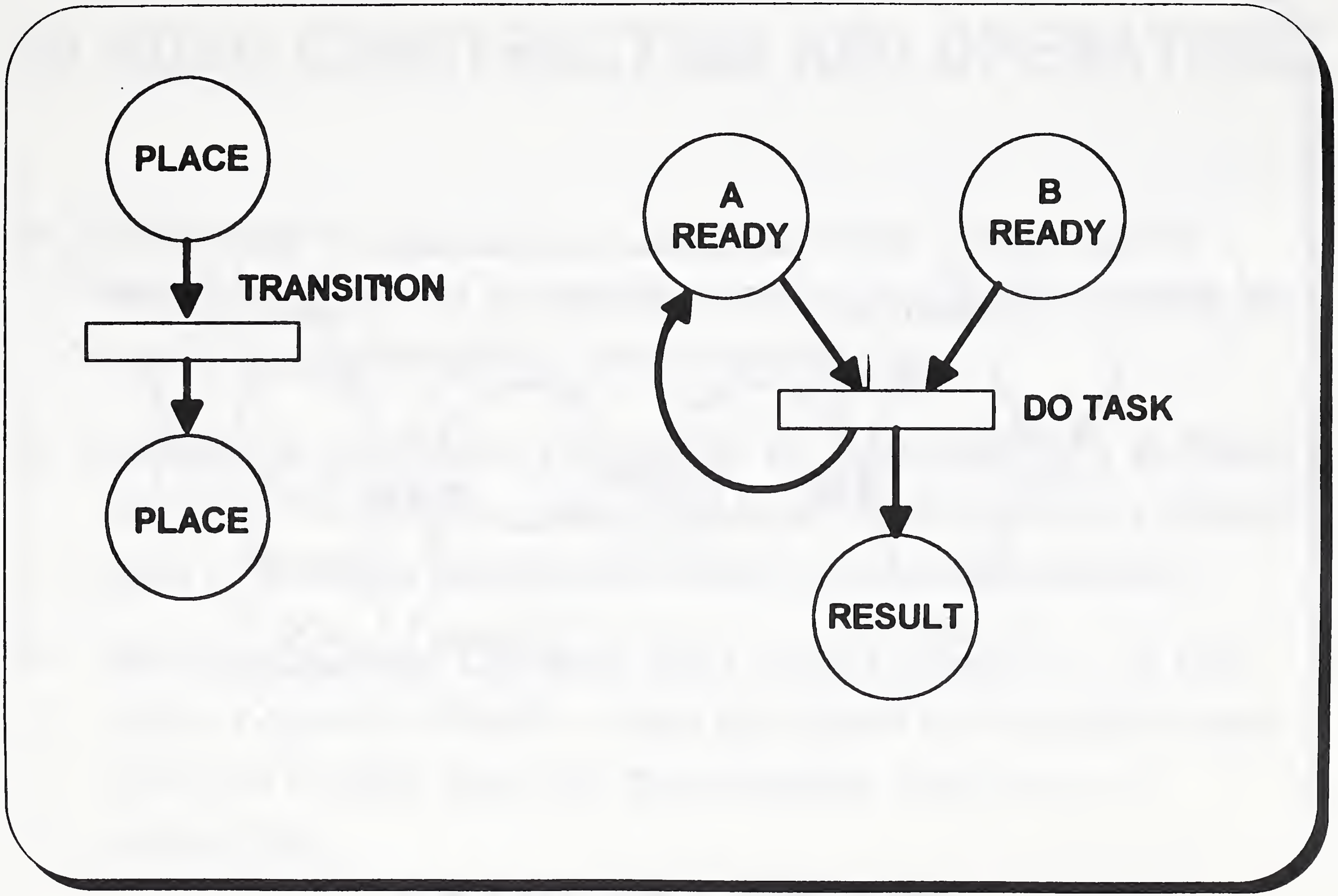
TOOLS FOR PLANNING: TASK LEVEL

- SIMULATION - New design methodologies embed simulation and visualization into the tools.

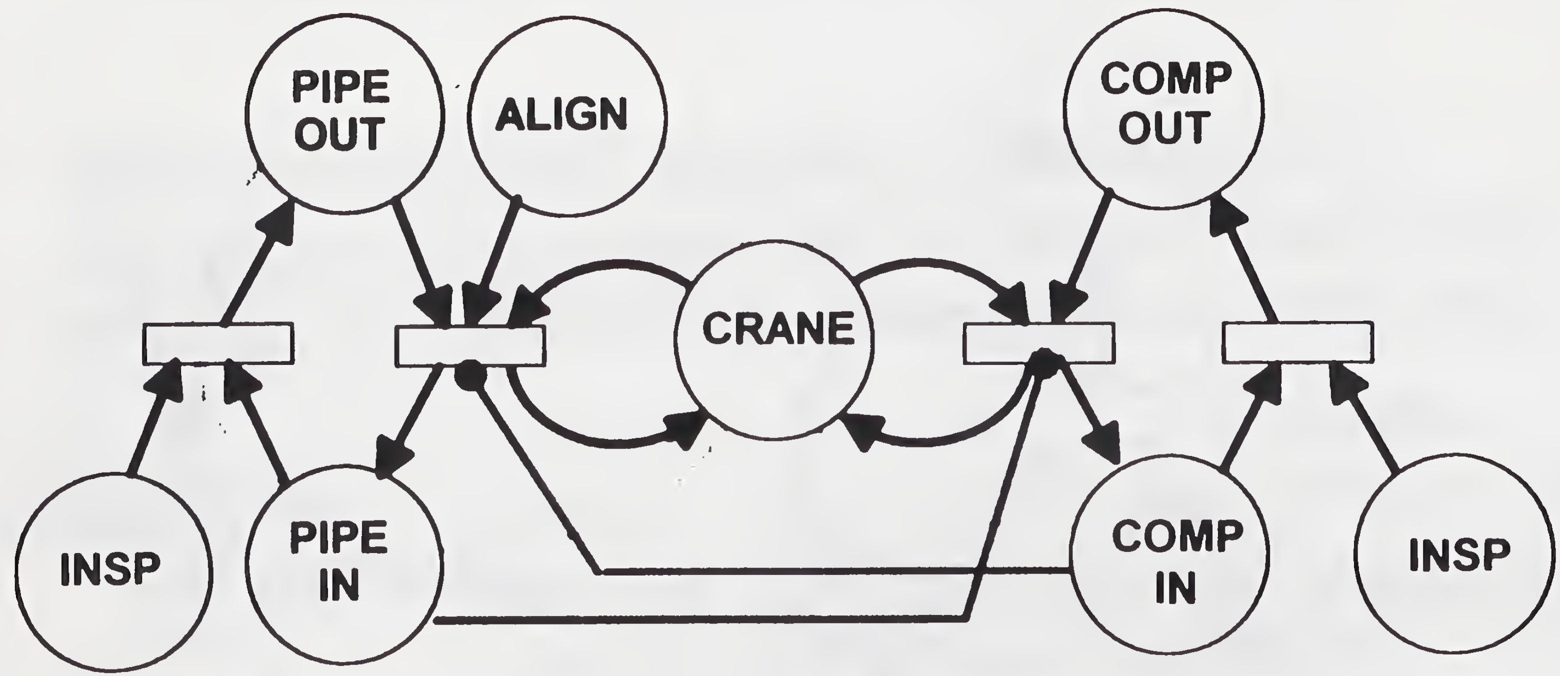
- DISCRETE EVENT MODELS: PETRI NETS - Methods which model and control coordination of events. Analysis tools to improve performance.

- MOTION PLANNING: COLLISION AVOIDANCE AND SAFETY - Planning safe and efficient motions to improve quality and safety.

PETRI NET MODEL



PETRI NET MODEL



EXAMPLES OF PETRI NET APPLICATIONS TO ROAD CONSTRUCTION AND OPERATIONS

- Planning of operations sequences - especially coordination of simultaneous operations such as loading, spreading, and monitoring.
- On-line supervisory control of operations - A Petri Net model maps naturally to a multidevice network and provides deadlock-free communications.
- Resource flow control and traffic control - A PN state representation may be used to monitor and control traffic flow or coordinate delivery of materials.

MULTIMACHINE INTEGRATION

- Many tasks require the cooperation of multiple machines - e.g. loading and spreading, cooperative lifting, positioning and sensing.
- Direct communication, or local network communication, would provide a basis for improved coordination --> improved quality, efficiency, and safety.
- Redefines the role of the operator and the needs for human interface. How do you monitor and control multiple interacting machines?

MOTION PLANNING

- EFFICIENT MOTION AND COLLISION AVOIDANCE

Motion plans based on an integrated site location system would improve quality (e.g. grading and surfacing) and reduce risks (e.g. collisions on site, or crane avoidance of power lines)

- REACTIVE PLANS AND SENSOR-BASED MOTION

Use of on-line sensing permits dynamic planning and reaction to changing conditions.

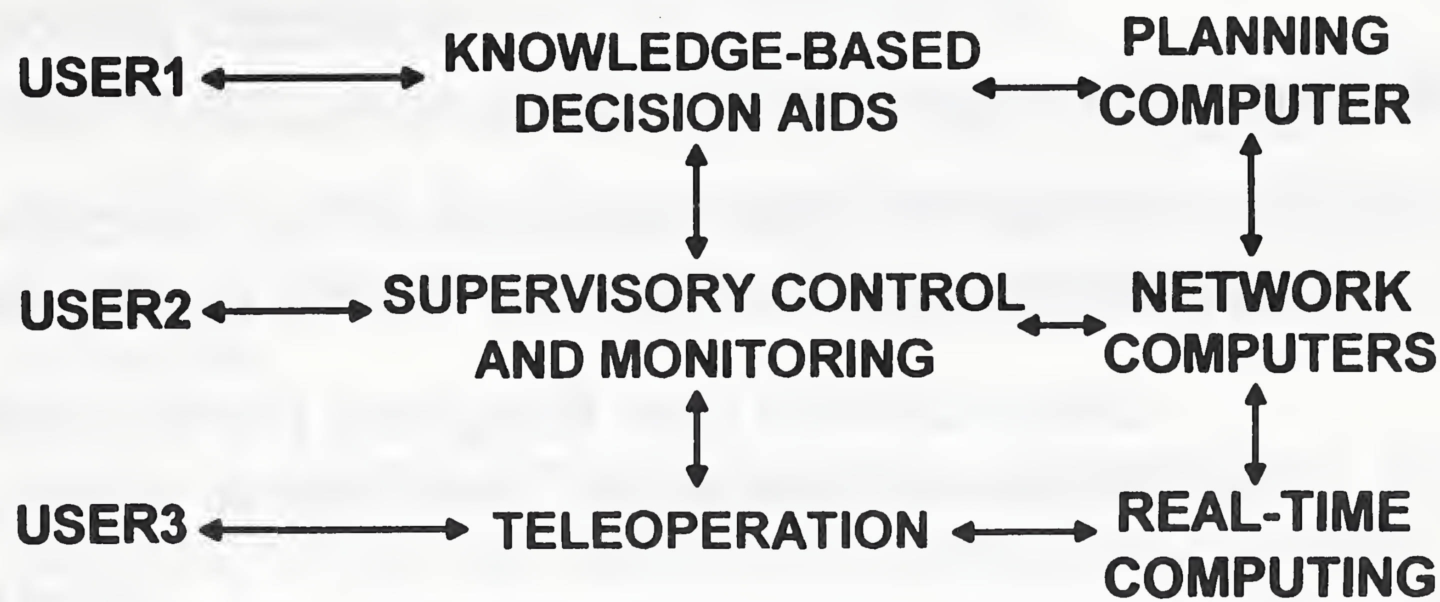
- SAFETY

Detection and avoidance of humans on the worksite.

SITE INTEGRATION AND HIERACHICAL CONTROL

PLANNING	DESIGN KNOWLEDGE BASE SITE AND RESOURCE CONSTRAINTS
COORDINATION	SPECIFIC OPERATIONS AND DISCRETE EVENTS DEVICE AND MATERIALS CONSTRAINTS
EXECUTION	MOTION AND SENSING DYNAMIC CONSTRAINTS

ARCHITECTURE OF ROBUST SYSTEMS



DESIGN FOR AUTOMATION

GOALS:

- Design of devices, parts, and materials for automated handling and construction
- Design of roads, structures, and bridges for efficient inspection and maintainance
- Design with improved, smart, and environmentally sound materials
- New design methods to improve simulation and visualization

SPECIAL CONSIDERATIONS IN ROAD CONSTRUCTION AND OPERATIONS

- Design, planning, and construction are carried out through bids, awards, and government procedures -- not the same as manufacturing.

- Standards and conventions widely affect the practice, and design and planning innovations must be demonstrated before acceptance is possible.

- Close coordination of agencies, contractors, and suppliers has not been the traditional mode of operation. New incentives for coordination and integration may be necessary.

SUMMARY OF OPPORTUNITIES

- Knowledge-based systems for planning, e.g. site layout and cost analysis.
- Petri net models for site coordination and networking, e.g. scheduling of machines and deliveries of materials, multimachine interaction.
- Hierarchical architectures for site integration of dynamic activities, e.g. sensor-based contour following for grading, teleoperated machines.
- Design for automation and new design tools for improved quality, efficiency, and safety, e.g. design of bridges for inspection and maintenance.

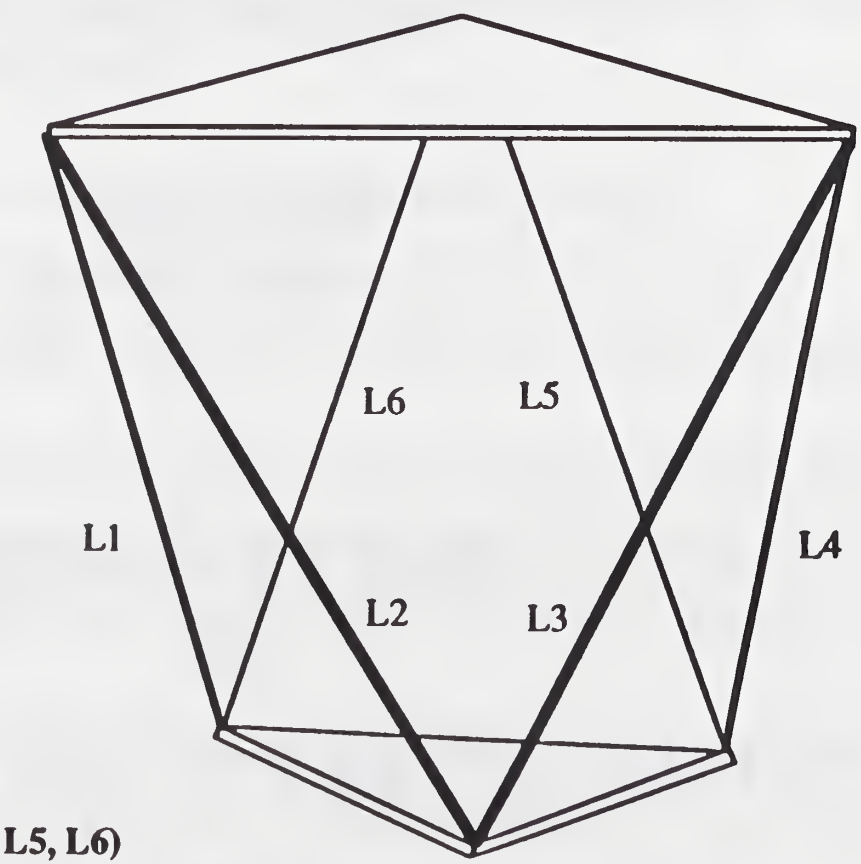
Precision Lift and Manipulation of Heavy Loads

Ken Goodwin
Jim Albus

Robot Systems Division
National Institute of Standards and Technology
Gaithersburg, Maryland

BASIC CONCEPT

STEWART PLATFORM



x, y, z, R, P, W = f(L1, L2, L3, L4, L5, L6)

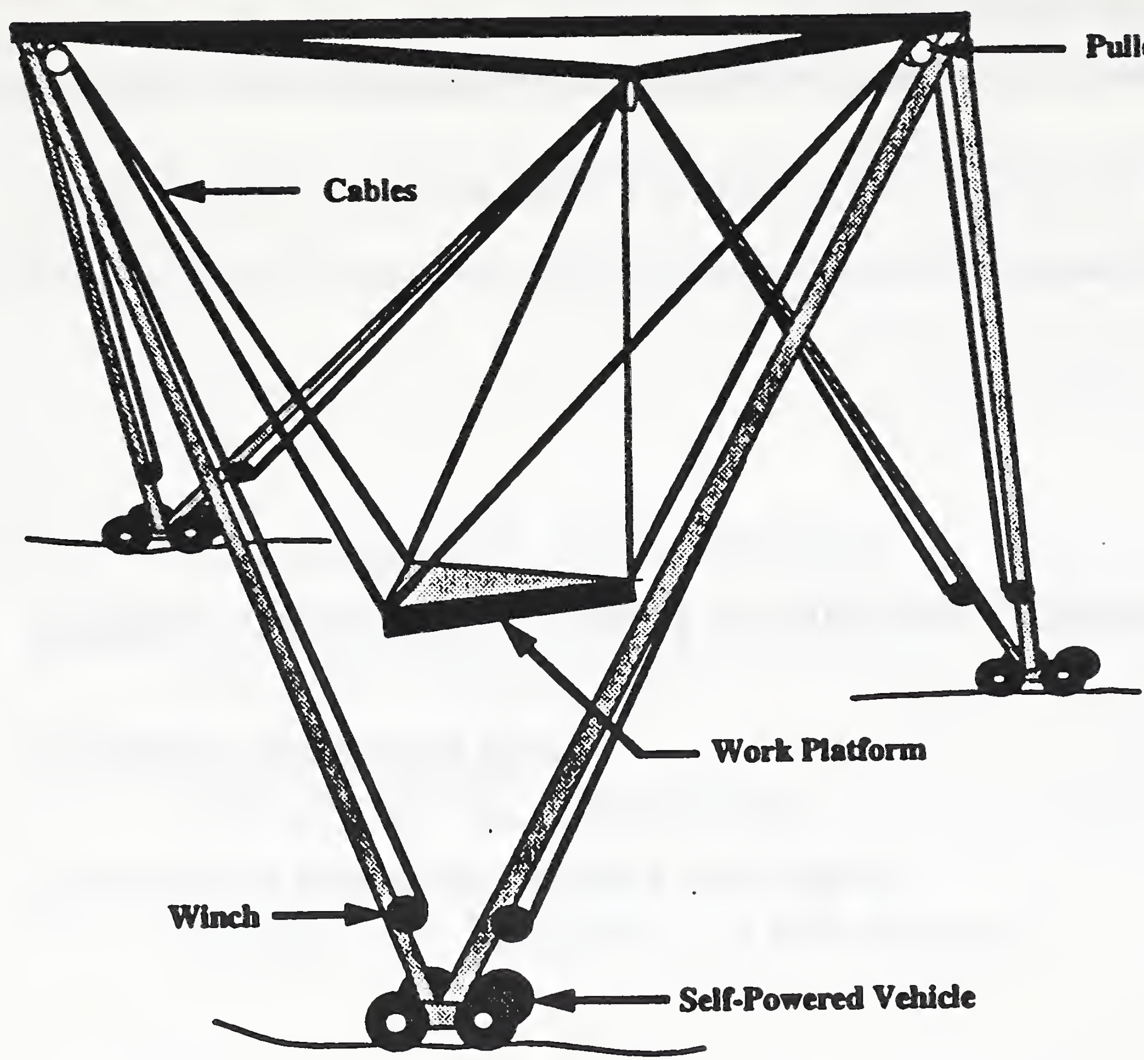


Figure 1. The NIST robot crane. An octahedron structure with an equilateral triangle at the top supports a work platform that can carry various tools or equipment. The work platform is suspended by six cables that are controlled by six winches.

APPLICATIONS

Steel or concrete beam erection

Bridge construction

Bridge inspection, paint stripping, repainting

STEEL OR CONCRETE BEAM ERECTION

Precision lift and position

ATLSS connector

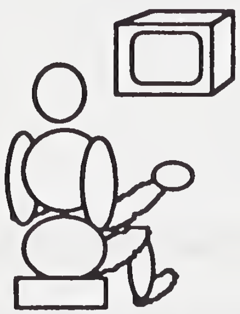
What can be done now

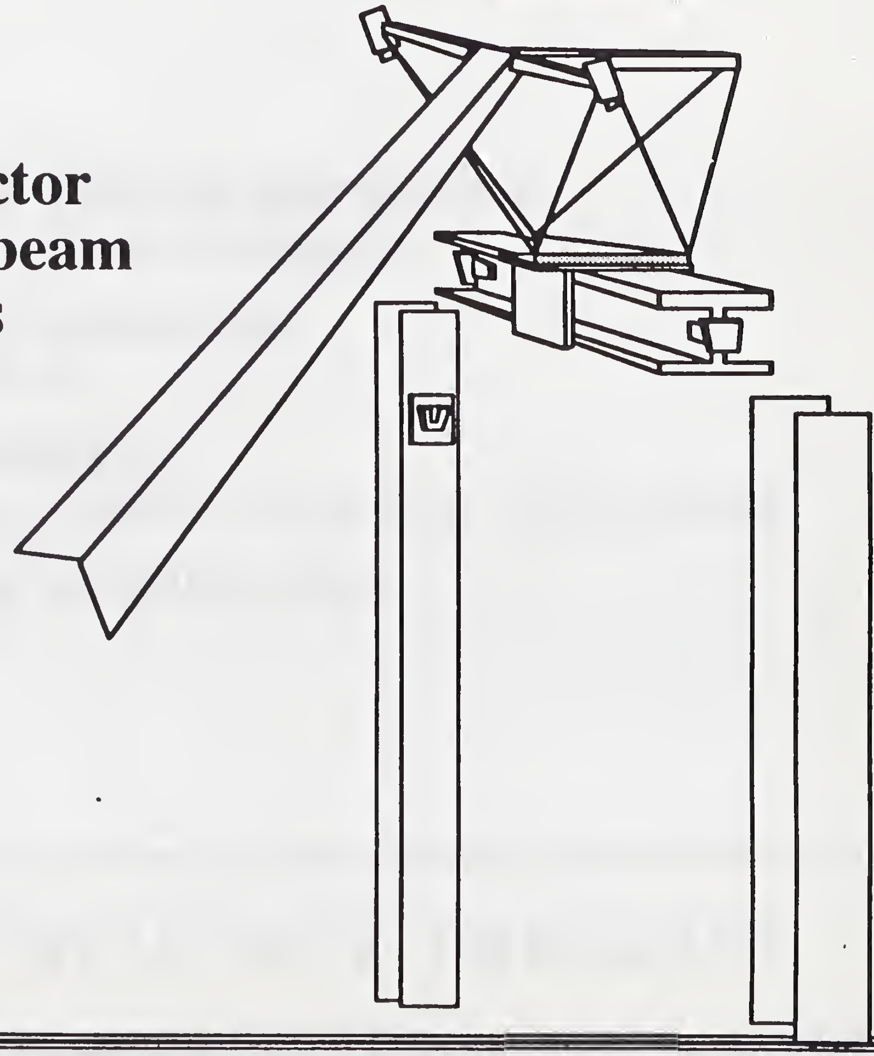
What can be done in the future

WHAT CAN BE DONE NOW

Teleoperation

- **Operator sees connector**
- **Controls position of beam**
- **May use TV cameras**
- **Human vision**

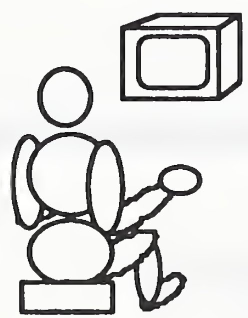


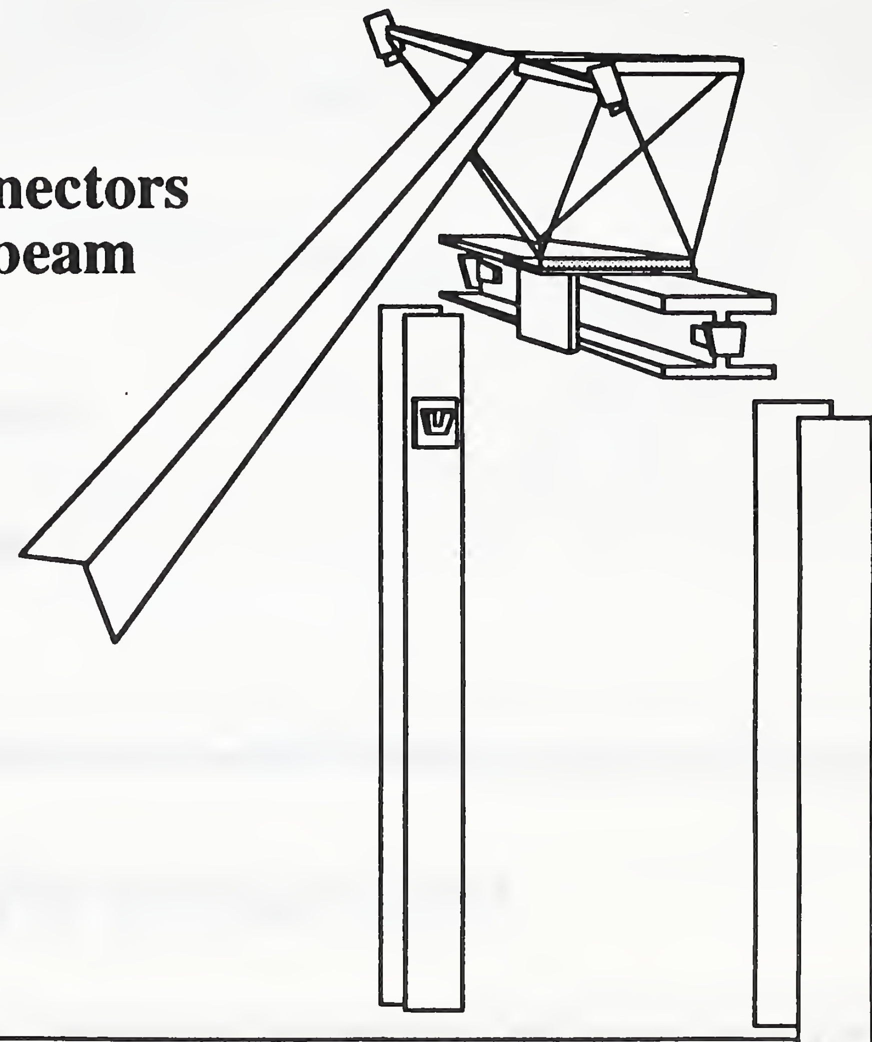


WHAT CAN BE DONE IN FUTURE

Semiautomatic

Operator selects connectors
Computer positions beam
Use TV cameras
Machine vision





Rapid Bridge Construction

Traffic Diversion

Wetlands Bridging

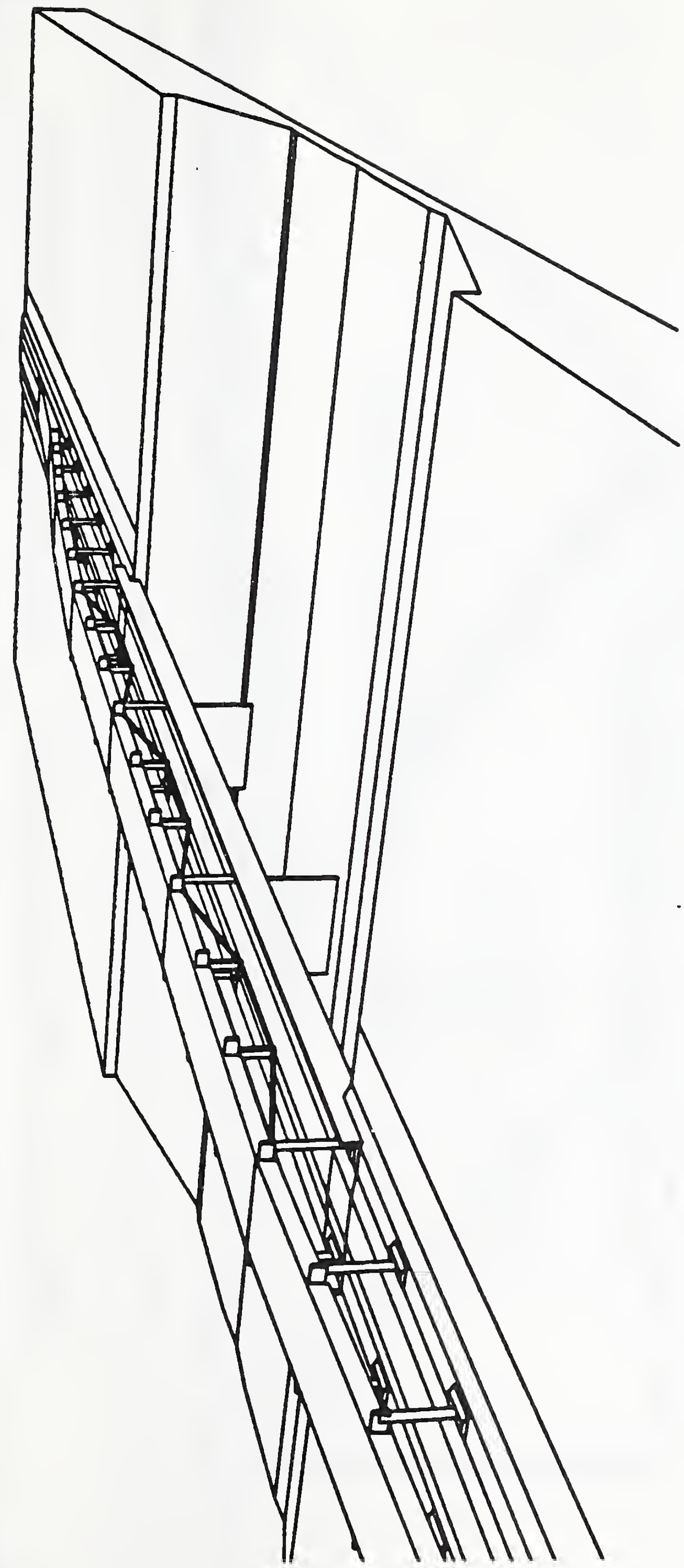
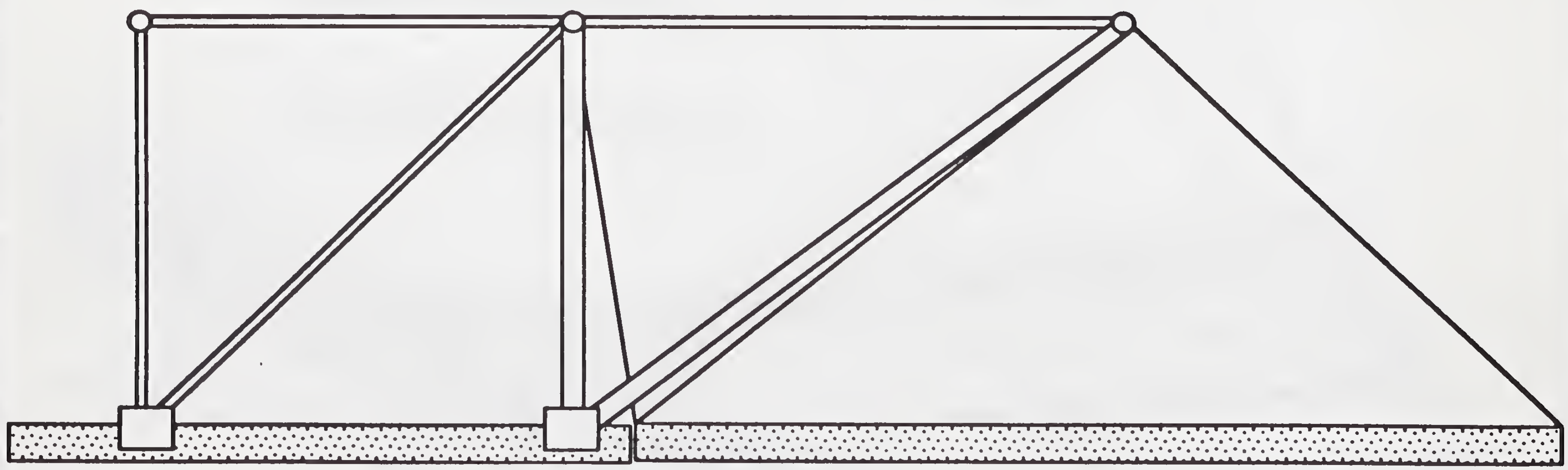


Fig. 8a : OVERPASS ABOVE BRIDGE REPAIR

General View

BRIDGE CONSTRUCTION

Light weight crane for erecting bridge elements



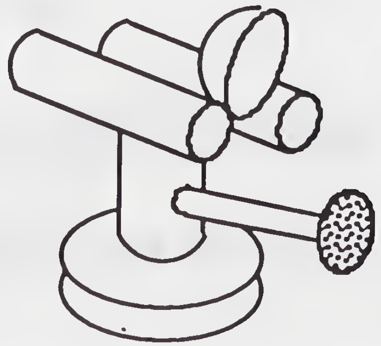
BRIDGE INSPECTION, PAINT STRIPPING

Near term developments needed:

- **High lift platform, joystick control**
- **Inspection heads**
- **Indexing vacuum shroud**
- **CAD programmed inspection**
- **Inspector programmed stripping**

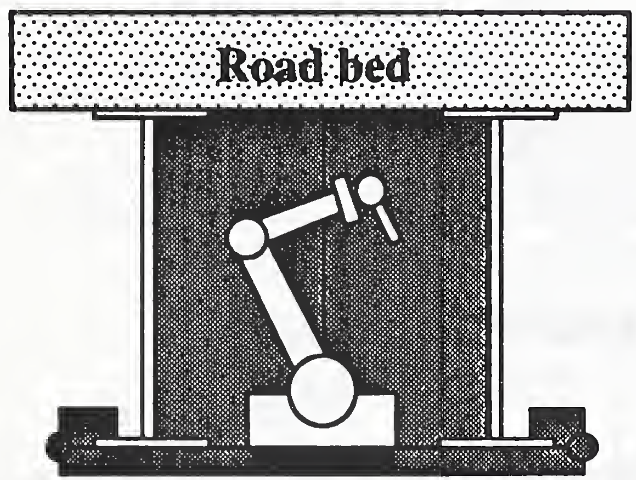
INSPECTION HEAD

Stereo pan / tilt head
Color cameras
Lighting
Retractable inspection tool

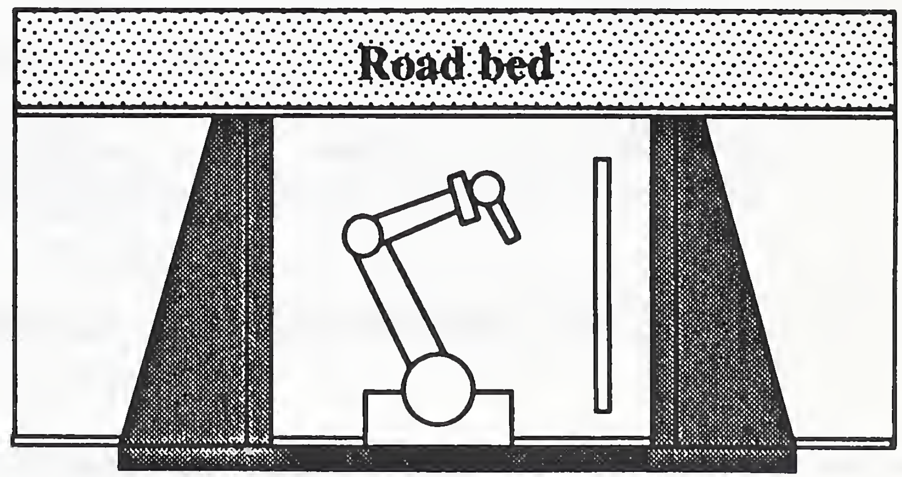


INDEXING SHROUD

Shroud clamps onto I-beams
Doors seal off section
Vacuum removes material
Robot moves blasting nozzel
Programmed from inspection data



End view

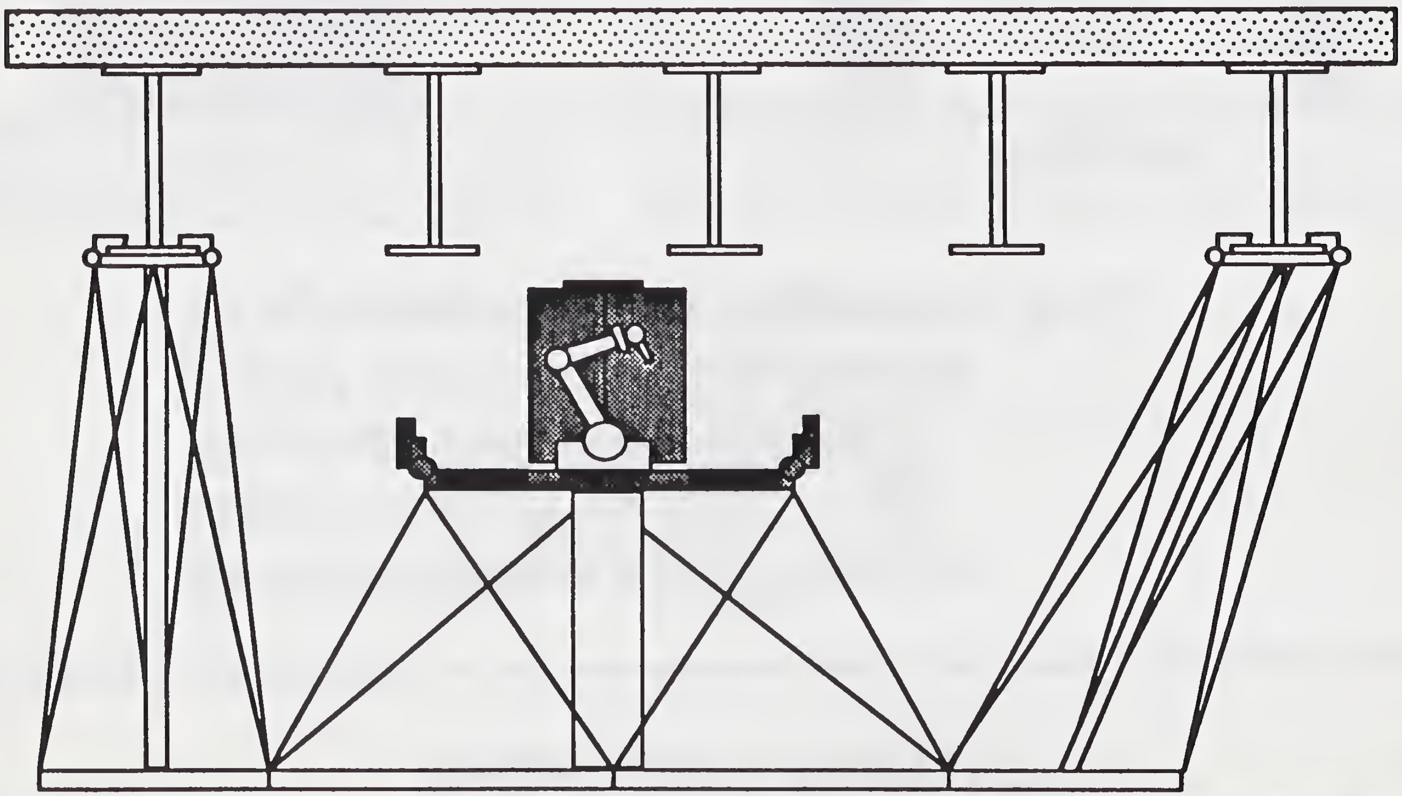


Side view

BRIDGE INSPECTION, PAINT STRIPPING

Long term

Walking gantry to carry shroud under bridge



Robotic Highway Overpass Stripping System

Development Steps :

- Identify Overpass Features
- Select Lift
- Select Blasting System
- Develop Shroud System
- Select Computer Configuration
- Design Manipulator Extension
- Develop User Interface
- Develop System Controller
- Integrate Aerial Lift and Extension
- Integrate Stripping System
- Perform Field Tests

SightPlan Model for Site Layout

By I. D. Tommelein,[1] Associate Member, ASCE, R. E. Levitt,[2] Member, ASCE, and B. Hayes-Roth[3]

Abstract: A model that uses artificial intelligence programming techniques is presented as a new tool for layout designers. This model, named SightPlan, represents the layout process as well as the layout product. A description of the knowledge and problem solving method is given of the SightPlan system that mimics the actions of a human layout designer. SightPlan lays out temporary facilities, represented as rectangles, on a construction site, represented as a two-dimensional space. An early commitment strategy and spatial constraint satisfaction techniques are used to find unique positions for facilities among those already in place. An example run in which SightPlan is applied to a case study project illustrates how the program operates in stand-alone mode. SightPlan demonstrates that knowledge-based systems can successfully address problems not adequately modeled until now and, thus, opens up a new way of thinking about computer-aided decision support for the construction industry. The present system is a prototype, however. Additional work must be done before SightPlan will be ready for field use and useful to field practitioners.

Introduction

The allocation of space to temporary facilities on construction sites has received little attention in modeling due to the complexity of the problem, resulting in a lack of optimization models, and the perceived marginal benefits to be gained from performing this task better. Yet, it is a routine task for many site engineers and project managers, and it is obvious that a site's layout affects worker travel time, activity interference, and, thus, productivity. Better layouts do pay off, if only managers could afford the time and effort needed for designing them.

A characterization of the site-layout problem and a thorough review of field practice and existing models lead to an understanding of the strengths and weaknesses of existing layout tools, so that a better model could be proposed. Model developers can essentially follow one of two approaches. They can learn what people do, model what people do, and develop tools that support people in what they do. Alternatively, they can build tools that approach the problem in a manner different from what people do, and possibly solve the problem in some better way. The first typically is the objective of cognitive scientists; the latter of engineers. In either case, constructing a model is meaningful because it helps identify the important factors, formulate the problem, study the interaction between factors, and understand alternative solutions. In the work that is presented here, the first approach is adopted.

This paper describes a model that mimics how people lay out construction

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sites. Details on the artificial intelligence (AI) programming techniques that were used for coding it as a computer system are given elsewhere (Tommelein 1989, 1992). A site-layout model adopting the engineering approach is contrasted with the present model in Tommelein et al. (1991). The generality of the model is assessed in Tommelein et al. (1992a).

Problem Description

The layout of temporary facilities is a routine construction management task. Once facilities needed to support construction operations are identified and their size and shape determined, they must be positioned within the boundaries of the available on-site or remote areas to meet multiple constraints and objectives related to safe and efficient operations.

Examples of temporary facilities are office and tool trailers, parking lots, warehouses, fabrication yards or buildings, staging areas, and lay-down areas. Such facilities usually remain in place for a period ranging from some days to several months and sometimes years (the duration of a construction activity or a major construction phase) and are, therefore, called temporary facilities. Despite their name, some temporary facilities are not dismantled after project completion and, instead, are reused for maintenance facilities during operation. Conversely, parts of the permanent structure may be built early so that they can be used for construction purposes.

Good site layouts meet multiple, though often conflicting, objectives. For example, reducing travel time may increase congestion. Managers who set out to meet several objectives must therefore prioritize them (a nontrivial and highly subjective task) and apply their priorities in constructing a layout (for which, sadly enough, no generally agreed upon method exists).

Substantial amounts of money can be tied up in temporary facilities, but it is hard to attribute project savings or avoided costs directly to layout decisions. Even so, layout costs are typically charged to project overhead, so no one eagerly pays for them. This makes it difficult to convince management that layout is an essential and indispensable planning task.

Space needs during construction are governed by the construction schedule, construction methods, and contractors' mobilization and demobilization of materials, equipment, and personnel on site. This tight interaction turns site layout into a complex problem. Practitioners dealing with it typically limit its complexity by treating site layout as an isolated problem after many other decisions have been made. Consequently, opportunities to construct good layouts are often passed up and bad layouts are recognized only when problems have arisen.

For the same reason, the present work focuses on the two-dimensional spatial location of temporary facilities on site. This is only part of the site-layout problem. In fact, one may argue that the other parts (including the selection, sizing, and shaping of temporary facilities) cannot reasonably be ignored; but this strong assumption is commonly made in layout modeling.

Existing Models

Practitioners typically sketch the layout of temporary facilities at different points in time on the site-arrangement blueprint. Fig. 1 shows such a site arrangement of the permanent facilities, marked up to show temporary facilities. Practitioners use this single drawing and rarely update it as construction progresses. As many changes are likely to occur, the drawing will become less valuable.

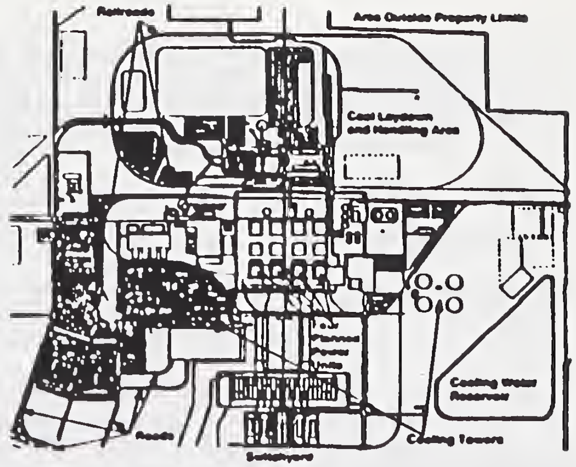

FIG. 1. Site Arrangement of Intermountain Power Project with Highlighted Long-Term Lay-Down Areas

The most popular aids for studying layouts are cut-out templates or other modeling blocks that people can move around to study space needs and assembly sequences (Henderson 1976). Many of the physical models have now been replaced by computer models (Rad 1982; Cleveland 1990; Reinschmidt and Zabilski 1990). Computerized product models have the additional advantage that they need not be limited to spatial representation; instead, they can be annotated and have more general functionality.

Other product models consist of anecdotal descriptions of specific site layouts (Tatum and Harris 1981; Weidemier 1986). These would be useful if more of them were available. At present, however, such descriptions do not provide meaningful, reusable layouts because they fail to elaborate on the specific context in which the layout applied, and one cannot gauge to what degree the subsumed knowledge is typical for the described or a new situation.

In contrast to product models, process models need no human assistance for generating a layout when given the appropriate inputs. Descriptive process models (Dressel 1963; Neil 1980, 1982; Popescu 1980; Rad and James 1983; Handa and Lang 1988, 1989) list facilities that may be needed, what types of steps a practitioner should consider in constructing a layout, while not specifying exactly which steps should be taken or in what order. This partial process specification is useful, yet insufficient to teach novices or program computers to become successful in constructing layouts.

Procedural process models typically involve heuristic construction or improvement methods (Francis and White 1974; Tompkins and White 1984; Kusiak and Heragu 1987). Although tested on construction applications, these operations-research (OR) type models are seldom used in practice (Rodriguez-Ramos 1982; Reinschmidt 1975). This is probably because they require large amounts of data about material flows between facilities and they are unrealistic in assuming steady-state conditions. Such data is difficult to obtain for operations where fixed travel paths may not exist and projects change over time as construction progresses.

There is a large discrepancy between tools and methods used in field practice and procedural models. Possible reasons why procedural models have not gained recognition in construction field practice include:

1. Expertise is required for selecting an appropriate model and formulating each layout problem. This expertise is quite different from field practitioners' know-how and may not be available, although knowledge-based systems can address this problem (Fisher 1984).
2. Substantial amounts of data are needed as input to these models. That information is not readily accessible to field practitioners, though it is possible to store vast amounts of generic or specialized data in a declarative system and make it available for multiple uses. In particular, this was advocated by Feigenbaum (1977) who coined the "knowledge is power" paradigm, and its usefulness has been demonstrated many times since. By pouring large amounts of domain-specific knowledge into a (computer) system, one can gain tremendous power and substantially cut the time to search for a solution, especially in cases where no effective, generic problem-solving algorithm is available.
3. Most mathematical models, implemented as black-box systems, follow procedures that are incomprehensible, counterintuitive, or questionable to users. More important, users cannot easily alter such models when the results are different from what they expect. They thus have to resort to a superficial tweaking of input data, that were not satisfactory to start with, to achieve the desired outcome. People resent situations in which they are held responsible for an outcome over which they have no authority. Woods (1986) identified the responsibility/authority double-bind by observing that when people refer to a human specialist, they generally pass on both authority and responsibility. If people are held responsible for a model's results, they should also have control over the selection and use of the model, even when this means that less-than-optimal models are thus preferred. Black-box models do not provide the practitioner with any means to gain insight into the process, nor do they allow the practitioner's intervention to make intuitive changes in order to lead to an acceptable solution, so practitioners oppose their use. The aim of much AI research has been to craft systems that are more transparent and easy to use. Rule-based systems have met this objective only in part. Ongoing research focuses on developing better interfaces and interruptible systems, so that users can interact with computers naturally and be in control.
4. If a user is forced into introducing many simplifications in order to be able to apply a model, it may take substantial effort to interpret the model's results within its broader context. The amount of effort spent may outweigh the value of the results.

Many of these are well-known shortcomings of procedural models and computer implementations (Vollman and Buffa 1966; Scriabin and Vergin 1975; Hollnagel et al. 1986). They explain why field managers prefer using simple, well-understood models to lay out sites over more abstract but potentially more powerful models. Keeping the limitations of existing models in mind, we set out to explore another modeling philosophy.

AI Modeling Philosophy

While existing tools help people construct layouts, they do not help model the human process itself of laying out a site. Modeling this process is desirable for the following reasons:

1. The quality and success of the process could be assessed, so as to allow for improvement, either in terms of the quality or quantity of input data, or in terms of the process itself.
2. Knowledge of the process could be made available to teach novices about site layout or to obtain feedback from managers now left out during the layout process.
3. When the process and all factors of importance are clearly stated, they could be taken into account in related construction-management decision-making.

These observations gave rise to the questions:

1. What are the logical steps that people take while laying out a site?
2. Do people have a systematic approach for laying out a site?
3. If so, is it possible to model this approach?

An AI-based approach to construction site layout was taken by Hamiani (1987), but a more sophisticated model is presented here. The present model, named SightPlan, mimics the layout process that people use and encodes the domain knowledge and heuristics they apply in this process (Tommelein et al. 1987a, 1987b).

SightPlan Model

Task Definition

SightPlan lays out about 25 facilities among approximately the same number of facilities that are in place. Each facility to be positioned is subjected to three constraints on average. As input to the system, all facilities are rectangular and specified by their dimensions or area, or by the facilities that they include as a grouping. In the latter case, it is part of SightPlan's task to dimension the grouping. Because space is abundant, all constraints on facilities' positions can be met, though not necessarily optimally. SightPlan's task is to determine the position(s) in two-dimensional orthogonal space of facilities relative to the site and permanent facilities, where they meet the imposed constraints.

Case Study

SightPlan's knowledge is modeled after two case studies. The Intermountain Power Project (IPP) and the model resulting from a layout protocol analysis are described in this paper. The American I Power Project (AM1) was used to validate the IPP model and to extend SightPlan's capabilities. More detail on AM1 is given in Tommelein (1989).

IPP is a coal-fired power plant designed for four units of 750 MW, two of which have been constructed. The plant is located in Delta, Utah on a site of about 1,850 acres (not including the area reserved for evaporation ponds) and provides electricity for Los Angeles, California. The project was planned by the Los Angeles Department of Water and Power (LADWP), the project manager. LADWP hired Black & Veatch architect-engineers (BV) for the design of the plant and contracted with Bechtel Construction (Bechtel) as construction managers. With 1,500 MW, constructed in a time span of six years, and at a construction cost of about $3.5 billion, this project is one of few of this size constructed in the 1980s. For more information on the successful construction of IPP, see (Boltz and Molinski 1987) and (Reinhardt 1987).

The following description is necessarily a simplification of the layout process as it was described by different parties. It captures the work of both the architect-engineers (AE) and the construction managers (CM) on IPP. Each party generated a layout design as needed for its specific task, so the result closely relates to the party's period of involvement and responsibility on the project.

Besides designing the permanent facilities, including power units, support buildings, permanent roads, and railroads, the AE laid out the temporary structures comprising warehouses, office buildings, first-aid facilities, entrance gates, brass alleys, security buildings, and management and labor parking lots. These are the buildings and support facilities needed for almost the entire duration of construction of the project, some of which would later be used for maintenance of the plant in operation. Of course, all structures associated with the construction workers' entrance to the site had to be grouped together. For practical reasons, many of the other long-term temporary facilities were clustered in the same area so that they would not cut up large open spaces on site that might be used by contractors for other purposes.

The AE also made rough estimates of needs for lay-down spaces for construction and anticipated their grouping on site. Accordingly, the AE extended the railroad and road grid to include construction railroads and roads. Upon completion of the design task, the AE produced the site-arrangement drawing, which was submitted together with a milestone schedule to the CM. As it turned out, the owners revised the scope of the project at the beginning of construction and decided to proceed with only two units instead of the planned four.

Part of the CM's task was to decide on the layout of the long-term lay-down areas for approximately 25 major contractors. The CM's lead mechanical coordinator was assigned to do this. Starting with the site-arrangement drawing, the CM identified all areas occupied with permanent facilities, all access roads, and all otherwise unavailable areas on site. From the site arrangement, the CM inferred which area the AE had anticipated for long-term lay down. Since unit 1 would go on-line before completion of unit 2, a section of the site to the southeast of unit 1 was reserved for plant operation and, thus, could not be used for long-term lay down. The area immediately surrounding the power units was kept open as a work area and for short-term lay down (the work area). A temporary railroad extension gave access to the southwest corner of the site, so all lay-down areas for contractor work on power units 1 and 2 would be concentrated in that so-called construction area. Contractors working on coal-handling facilities would be located in the coal storage area. Material lay-down for the cooling towers and circulation water piping would be located near the cooling towers.

For each contractor, the CM specified the needed area, identified access requirements, determined whether or not major pieces of material would need to be moved to and from the lay-down area, and established how critical the contractor's activity was. Based on this information, the CM ranked the areas by overall importance and picked the one ranked first to find an appropriate location for it on site. This meant determining in what area that lay down had to be (i.e., meeting a zoning constraint), determining whether or not the lay down needed to be adjacent to a railroad (adjacency constraint), and making sure that it did not overlap with roads or any of the fixed facilities on site (nonoverlap constraint). Finally, if several alternative positions remained that met these constraints, the CM satisfied the preference of the contractor to be as close as possible to the place of installation of the work in the permanent facility by picking the best (as-close-as-possible constraint, computed based on shortest distance) position from the remaining alternatives. Then, the CM repeated this process with the second contractor's lay down, and so on. The results of this process were finalized by highlighting and labeling areas on the site-arrangement drawing (Fig. 1).

Before the award of contracts, contractors bidding the job were told what area would be available to lay down materials on site, so they could plan their work and further subdivide their assigned areas to specifically accommodate individual needs. The aforementioned description is necessarily a caricature of the layout process applied at the IPP site, but it is what was implemented in SightPlan.

Model Description

SightPlan's model builds upon the blackboard knowledge-based system architecture for cooperative problem solving (Hayes-Roth 1985; Engelmore and Morgan 1988). *Blackboard architecture* refers to the structure and mode of operation of a specific type of computer program. Different implementations of this architecture exist, such as the BB1 architecture that was used for SightPlan (Hewett 1988).

The following analogy applies between the system's operation and the setting of a meeting at which a problem is to be solved. At any one time, different meeting participants (called knowledge sources) may suggest contributions to solve the problem that is stated on the blackboard (a common data structure), but only one participant at a time will get to make a change. To select one of several changes that may have been proposed at once, the moderator (called scheduler) gauges each participant's potential contribution against an explicitly stated problem-solving strategy. After determining the change that best matches the strategy's prescription, the moderator proposes to allow that change to be made. In addition, the user of the system can either agree with the moderator's choice, or disagree and propose an alternate change. The user has the final word on which change gets executed and effectively acts as another participant in the system.

SightPlan uses this mechanism of considering all possible actions at a cycle and selecting the best one in accordance with a strategy to construct layouts. To do so, it needs two types of knowledge. First, it must know which objects are to be positioned and which constraints they must be subjected to. Second, it must have a strategy.

The following project-specific data pertaining to objects and constraints on IPP is input to SightPlan:

- Major permanent facilities on site with their dimensions (rectangular in shape; possibly including some surrounding area) and location.
- Access roads and railroads with their dimensions and location.

- Long-term temporary facilities with their dimensions (location to be determined).
- Long-term lay-down areas with their dimensions (location to be determined).
- Constraints on the location of temporary facilities and lay-down areas relative to the permanent facilities and roads (e g., constraints describe whether facilities need to be adjacent to a road or railroad, or which permanent facility a lay down must be close to)
- Zones that partition the site in smaller areas (including the work, coal, operations, and construction area).

The early-commitment strategy, learned from the AE and CM in the case study, is also input to SightPlan. This so-called expert strategy is encoded as a skeletal plan that prescribes the types of actions SightPlan ought to take and their sequence for layout of a power plant site. This strategy captures the strategic expertise of a field engineer who knows how to lay out such sites. In essence, it prescribes that one must start by identifying the space occupied by permanent facilities, that temporary facilities on site for the entire duration of construction should be positioned first, followed by shorter-term facilities, and that larger objects should be positioned before smaller ones. Thus, this strategy is not project-specific; it is rather general in that it can be used to lay out other construction sites as well. Fig. 2 illustrates this strategy's skeletal plan.

Table 1 lists some of SightPlan's actions while pursuing the expert strategy on IPP. Column 1 gives the system's execution cycle numbers. Column 2 outlines SightPlan's action corresponding to each cycle. In the remainder

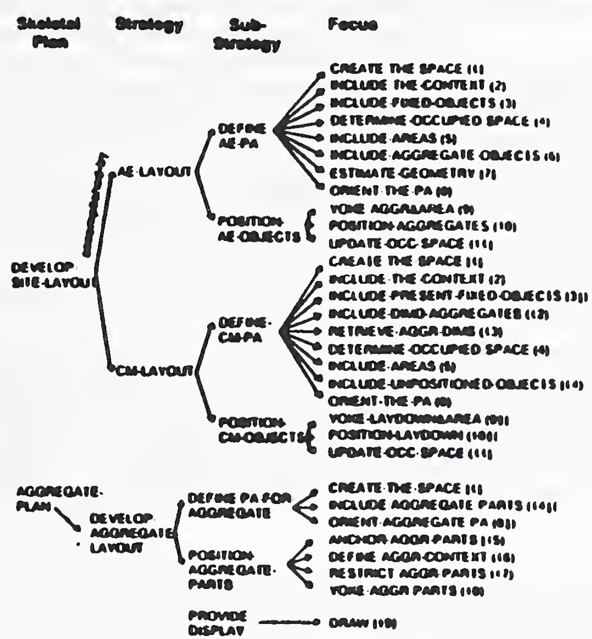

FIG. 2. Skeletal Plan of Expert Strategy Applied to IPP

TABLE 1. Some Cycles from SightPlan's Expert Strategy Applied to IPP

Cycle (1)	Action (2)
	(a) Architect-Engineers
14	create pa1
19	include context in pa1
24	include fixed objects in pa1
29-30	include and identify occupied space in pa1
34-37	includes areas in pa1
43	include first aggregate in pa1
44	size aggregate context
45	shape aggregate context
47	include second aggregate in pa1
48	select aggregate layout plan
55	create pa2
60-72	include object in pa2
77	orient pa2
82-136	anchor object in pa2
142	shape context pa2
145	transfer size from aggregate context in pa2 to aggregate in pa1
152	orient pa1
158-165	position first aggregate in pa1
167-175	position second aggregate in pa1
182-194	refine pa2
	(b) Construction Managers
14	create pa1
19	include context in pa1
24	include fixed objects in pa1
29	include and identify occupied space in pa1
33-36	include areas in pa1
40	include laydowns in pa1
44	orient pa1
50-136	position objects in zone or outside of zone in pa1
138-188	position objects so that they don't overlap with permanent facilities
190-293	position large objects first, with as close as possible constraints, then update occupied space and proceed with following object

of the paper, discussion is focused on a few specific cycles and actions. For a full description of the expert layout strategy, please refer to (Tommelein 1989).

During knowledge acquisition, we found that the AE and the CM each laid out part of the temporary facilities on IPP. This division of tasks is reflected in the layout strategy: the AE-layout precedes the CM-layout (Fig. 2 and Table 1). Many of the strategic steps of the AE, however, were quite similar to those of the CM. Identical numbers in parentheses following each focus in the skeletal plan reflect this apparent duplication of effort. Yet, the objects involved in the actions of the AE are different from those of the CM. For example, Table 1 reflects the same action for the AE as for the CM at their respective cycle 24 (include fixed objects in partial arrangement [PA]1). Fixed objects for the AE are the permanent power plant facilities; temporary objects for the AE are the warehouses and construction management office buildings that they design and also locate. Fixed objects for the CM, however, are the permanent power plant facilities as well as the warehouses and construction management office buildings located by the AE, whereas temporary objects for the CM are the long-term lay-down areas for contractors. The English-like sentences of the layout steps shown in Table 1 clearly describe SightPlan's actions.

SightPlan in Operation

Screen dumps illustrate how SightPlan constructs a solution. In parentheses are the cycle number and the corresponding action's description.

SightPlan creates a first partial arrangement (14—create PA1) and defines the boundaries of the space to be laid out (19—include context in PA1). The system then includes the fixed objects (24—include fixed objects in PA1) (Fig. 3). It identifies the groupings of objects, called aggregate objects, and includes them (43—include first aggregate in PA1 and 47—include second aggregate in PA1). Because these groupings do not have a shape nor dimensions, SightPlan must first take some steps to determine those, before the aggregates (IPP-construction-facilities and IPP-construction-entrance) can be displayed (Fig. 4). The substrategy that SightPlan calls to shape and size the IPP-construction-entrance groupings is shown as the aggregate-plan in Fig. 2, but discussing its operation is not done here. Interested readers can refer to Tommelein (1989) for more detail.

After that is done, SightPlan can position each of the aggregates in PA1 by sequentially meeting less stringent constraints, as is prescribed by its strategy (158–165—position first aggregate in PA1) (Figs. 4 and 5) (167–175—position second aggregate in PA1) (Fig. 5).

When the AE layout is complete, SightPlan uses the result as input for the CM layout. All facilities shown on the AE layout are now treated as fixed. (Before construction started, the project owners decided to build only two 750-MW units instead of the planned four. These actual units are shown as two black rectangles in Fig. 6, whereas Fig. 5 showed four.)

The CM starts by creating a new partial arrangement (14—create PA1), including the site boundaries within which they have to work (19—include context in PA1) and what they consider to be permanent facilities (24—

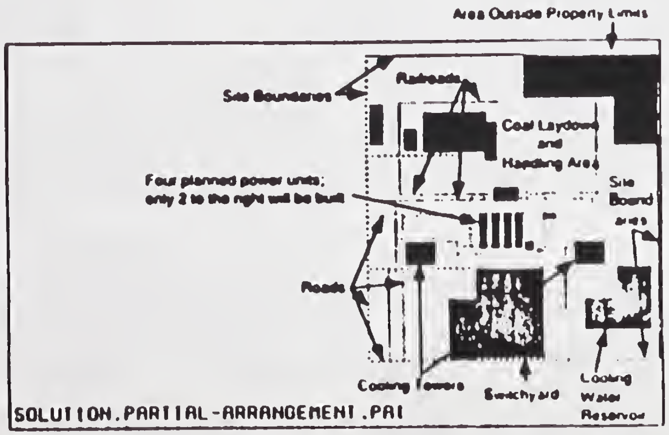

FIG. 3. SightPlan Includes All Permanent Facilities on IPP

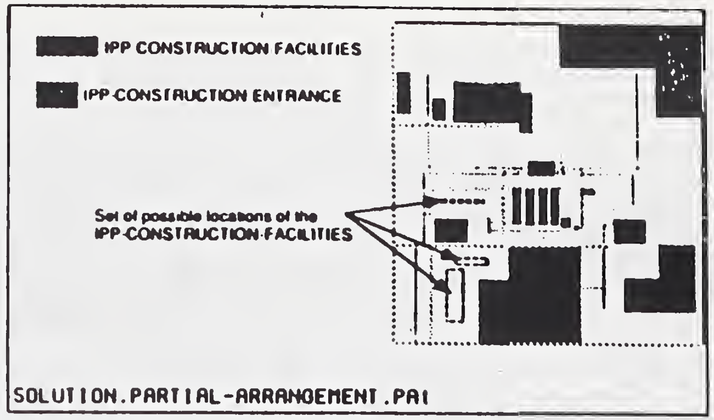

FIG. 4. Two Shaped and Sized Aggregates in PA1. IPP-Construction-Facilities Has Met All Constraints Except Preference Constraint as-Close-as-Possible to Power-Unit-1

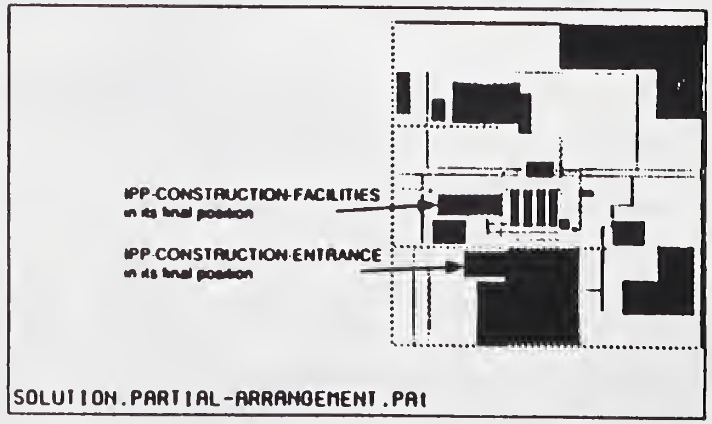

FIG. 5. SightPlan's Solution to AE's Layout Task on IPP

include fixed objects in PA1). SightPlan then zones the site into four areas (33–36—include areas in PA1) (Fig. 6):

1. The work area, immediately surrounding the power units, to be used for short-term lay down.
2. The coal area, where the coal-handling facilities are, to be used to locate all contractors constructing these facilities.
3. The operations area, located to the southeast of unit 1, to remain accessible at unit 1 start-up when unit 2 still is under construction.
4. The construction area, to the southwest of the site, where all contractors involved in construction of units 1 and 2 will be grouped.

SightPlan then includes temporary facilities (40—include laydowns in

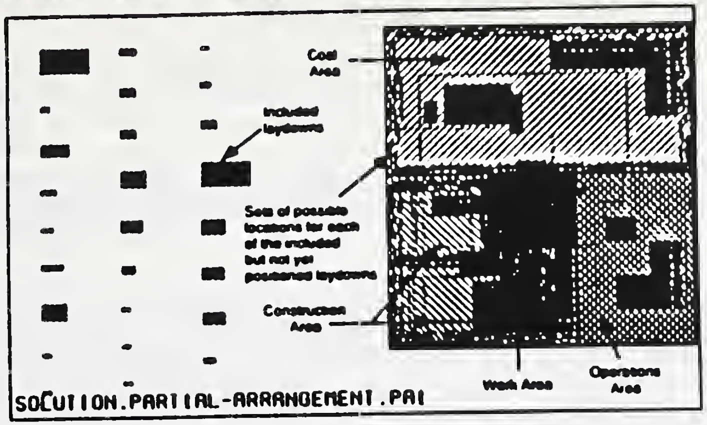

FIG. 6. SightPlan Zones Site in Four CM-Specified Areas and Includes All Lay-Downs in PA1 for Layout by CM

PA1) (Fig 6) and positions each lay-down area in the appropriate zone (50–136—position objects in zone or outside of zone in PA1) (Fig. 7).

The program can then position each lay-down area by sequentially meeting less stringent constraints, as is determined by the strategy (138–188—position objects so they do not overlap with permanent facilities in PA1 and 190–293—position large objects first in PA1, with as-close-as-possible constraints, then update occupied space and proceed with following object). SightPlan stops when no more executable actions remain (Fig. 8). In this way, it has computed possible locations for each of the facilities that needed to be positioned and has thus satisfactorily completed its task.

Implementation

SightPlan is implemented in Common Lisp using BB1 version 2.1 running on a Texas Instruments Explorer. Its system code is available from the Civil and Environmental Engineering Department at the University of Michigan and from the Center of Integrated Facilities Engineering at Stanford University. A license to the BB1 development environment must be obtained from Stanford's Office of Technology Licensing.

Lessons Learned

SightPlan's Capabilities

The SightPlan model shows that it is feasible for a computer program to mimic the steps taken by a field practitioner for laying out a construction site. The model takes into account more factors than other construction site-layout models have done so far, including objects classified by type, spatial, and temporal characteristics, and constraints expressing requirements or preferences. SightPlan is in that sense a more realistic model than other models are.

SightPlan's operation is easy to follow not only by AI researchers, but also by field practitioners. This was empirically assessed by having the construction manager of IPP observe the program. It only took a short introduction to clarify the operation of the system and our manager could easily comment on the program during its run and critique its actions and the

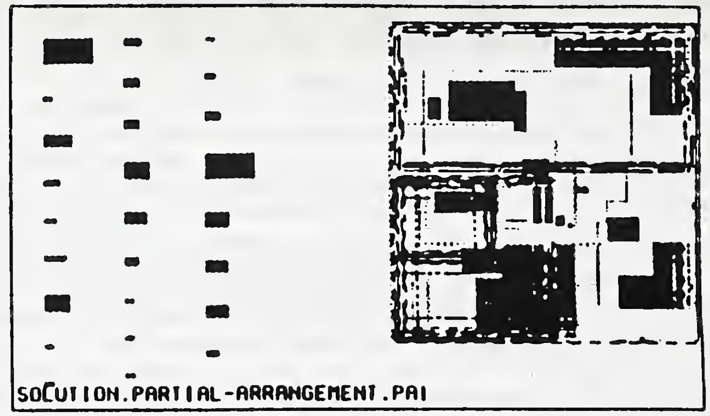

FIG. 7. All Lay-Downs Meet Their Zoning Constraints

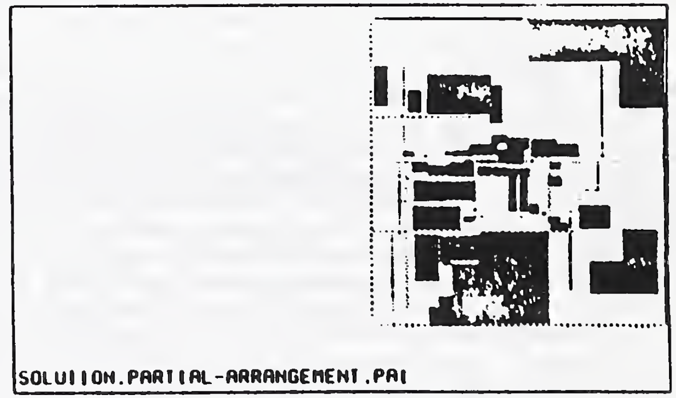

FIG. 8. SightPlan's Solution to CM's Layout Task on IPP

resulting layouts. The following step in assessing the transparency of the system is to have field practitioners use it. SightPlan's current implementation does not easily lend itself to that.

Clearly, SightPlan does not capture all expertise used by practitioners for addressing the layout task, and, in fact, that would be impossible. In particular, human's spatial reasoning, emulated by SightPlan as constraint satisfaction, is arguably modeled satisfactorily. When natural language can remain vague, SightPlan's constraints had to be forced into unambiguous spatial propositions. SightPlan's knowledge is different from that of human practitioners, who rely to a large extent on visual inspection and frequently use graphical and physical models for constructing and evaluating layouts. Early on in this work it became clear that a graphical display would be essential for debugging the program and communicating the layout to other people. Accordingly, the graphical display system was developed, of which screen dumps were used to illustrate this paper.

Beyond mimicry and unlike most other systems, SightPlan explicitly represents the practitioner's layout strategy, so the system knows what it is doing. The major advantage of this is that the strategy exhibits generality, to the extent that it can be reused to construct layouts for new sites. When the objects and constraints related to IPP are replaced by those on a new site, SightPlan's strategy will create a layout for the corresponding new problem. This was confirmed using data from AMI (Tommelein 1989). Only minor changes were needed for the transferred strategy to be operational. The expert strategy is, thus, a first step towards articulating a strategy that could be applied on different projects and taught to novice practitioners.

The current implementation of SightPlan is nowhere close to outperforming field practitioners. For example, when supplied with all necessary data, IPP's expert took several hours, but less than a day, to lay out the site (more exact data is not available). Faced with the same problem, but likely supplied with less knowledge to take into account, SightPlan constructs its layout for IPP in about three hours. The program is slow, in part because it has not been implemented or optimized for speedy performance. Much intermediate data is kept around for process verification and analysis. While acquiring data is tedious and unavoidable in either automated or manual layout approach, crafting SightPlan's knowledge base takes additional time.

SightPlan's output (Fig. 8) can be compared with the expert's (Fig. 1). The layouts necessary look similar, as SightPlan's constraints reflect those specified by the expert. By virtue of ignoring a number of factors (such as site elevation and underground utilities), SightPlan's layout must be of inferior quality. Assessing the quality of any layout is difficult, however. If an evaluation procedure would be available to replace visual inspection, computer programs could explore more alternatives and potentially find better layouts than people could.

For SightPlan to become field-usable, it must be made both practical and readily available. Field practitioners may want to mirror their expertise in the model, in order to obtain a (perceived) knowledgeable assistant. Automated knowledge-acquisition tools (of which research prototypes exist) could aid them in creating knowledge bases. If SightPlan's strategy is not satisfactory, the user can override it by choosing alternate actions from the SightPlan agenda or using the graphical interface to narrow sets of positions (Tommelein et al. 1991). Learning programs (of which research prototypes exist) could then extract the user's strategy for subsequent automation (Confrey and Hayes-Roth 1990; Gans and Hayes-Roth 1990). Improving availability means reimplementing the system on hardware available on construction sites and optimizing its execution speed. These are both feasible.

Computer-based models for the site-layout process and product have potentially major advantages over other models, though. Computer programs can easily be updated by one or several sources as construction progresses and interface with other programs. The ability to maintain current site data (e.g., to reflect material delivery, construction execution status, and schedule changes) may tremendously improve materials management practice.

SightPlan's Scope

SightPlan's task-specific knowledge solves the carefully bounded layout problem and appears to be largely applicable to the underconstrained problems encountered at IPP and AMI. While it is useful for addressing the task at hand, it is insufficient for addressing other tasks. Additional or different types of knowledge would be required to deal with overconstrained site layouts such as those of downtown building construction sites or to allow

reuse of space over time, taking into account the criticality of activities based on the construction schedule.

Field practitioners often recall parts of previous layouts and integrate such case-based knowledge into the solution process. SightPlan starts each solution process from scratch, and does not learn from previously successful (partial) arrangements, i.e., it does not perform case-based reasoning.

The present work focuses on the allocation of space to long-term facilities and ignores shorter-term facilities. This is not to say that short-term facilities are not important. In fact, assigning short-term staging areas is often crucial as delays directly impact the construction schedule. In doing layout, managers leave open critical areas for staging and equipment access. Explicitly, reasoning about the assignment of space over time that is needed to deal with mobile equipment, for example, is beyond SightPlan's current scope.

In summary, SightPlan exhibits the brittleness that most AI programs are blamed for. In fact, most procedural programs exhibit the same type of brittleness. However, SightPlan's implementation architecture has been used to successfully model other tasks. In addition, the opportunism that is innate in the BB1 architecture lends itself well to extending the system with additional knowledge sources to address increasing complexity. Expanding SightPlan's task in an integrated or distributed manner is thus possible.

Although it was stressed that SightPlan would gain power by knowing more about the domain of the task it tackles, its knowledge about power plant construction is not that domain-specific. SightPlan differentiates facilities based on, for example, their dimensions. Dimensions are a characteristic of objects in many domains and appear to be a fundamental concept in the layout task. As with many AI systems, however, SightPlan gains power by using a classification of objects according to their type, which is where the domain specificity is key. For example, all individual contractor lay-down areas belong to the same parent class lay-down areas. SightPlan's strategy uses this classification knowledge by referring to the class, rather than to individuals. In this way, the strategy remains unaffected when individual contractor lay-down areas of one, get replaced by those of another project. SightPlan could, thus, be applied to layout problems in other domains.

Modeling Philosophy

An issue not raised in this paper is whether the expert strategy is necessarily best for a computer system to follow. Clearly, this issue resurfaces every time a knowledge-based expert system is built, and one questions the quality and validity of expertise. One cannot assume that a descriptive knowledge system will lead to desirable results when it is used prescriptively. Thanks to the flexibility of SightPlan's implementation environment, alternate strategies could be tried that might better suit the available computational power. Experimentation led to such a strategy, using postponed commitment (Tommelein et al. 1991). A computer program need not commit to finding a single position of one object at a time before proceeding with the next object because it does not exhibit the same cognitive limitations as people. Instead, computers can easily keep track of sets of alternate positions, gradually constrain those, sample multiple positions after all hard constraints have been met, and generate combinations of satisfactory layouts. The postponed commitment strategy together with a graphical interface for users to change layouts interactively while solutions are constructed delivers proof of concept that we can build powerful decision support tools to assist field practitioners with layout design.

Conclusions

The allocation of space to temporary facilities on construction sites was identified as a task for which no good process and few product models exist. The discrepancy between tool availability and tool use was ascribed to the difficulty of identifying the appropriate tool to suit a new situation, the need for large amounts of input data for tools to be usable, the opaqueness of most tools, and the difficulty of realistically interpreting the solutions to highly tailored problems. To overcome some of these shortcomings and better understand what people do, the SightPlan system was implemented to mimic the actions of field practitioners laying out construction sites. The strengths of this model are that it not only closely approximates the practitioner's layout process and solution layout, making the model easy to follow, but it explicitly represents a strategy that can be reused to lay out other sites. The fully implemented model was tested on only two case studies, so further testing is needed to strengthen and validate claims of generality and practicality.

Acknowledgments

This paper summarizes work on site-layout modeling that was part of Iris Tommelein's doctoral research, advised by Ray Levitt and Barbara Hayes-Roth at Stanford University. Many thanks are owed to the articulate and enthusiastic group of engineers and managers from the Los Angeles Department of Water and Power, Bechtel, Black & Veatch, and Stone & Webster for their time and patience in posing challenging questions pertaining to site layout, explaining layout approaches, and granting permission to reproduce company documents and blueprints. M. Vaughan Johnson enthusiastically helped build the first SightPlan prototype. Michael Hewett made many thoughtful suggestions for implementing features and hacks. Former PROTEAN members willingly discussed their representation and reasoning about arrangement problems, and Tony Confrey and François Daube assisted in designing and coding SightPlan's constraint engine.

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Automation Integration for Construction

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Abstract
When compared to engineering design, the use of automation in construction is still fairly limited. The applications of automation to construction have largely been focused in the general area of project management for activities such as scheduling, manpower tracking, billing, materials control, etc. Since the advent of powerful personal computers, these technologies are routinely used at construction sites. However, with the increased use of 3D modeling in the design process, coupled with the increased availability of cost effective hardware and software, there are now many opportunities for strategically new applications of automation to construction. In this discussion, we will focus on two very specific examples of new uses of automation. Both of these applications are currently underway for a major transportation projection. The first application is the integration of project schedule information with 3D animation. This application makes it possible to see and compare various schedule alternatives in a 3D real-time animated mode. The second application is the extension of 3D real-time animation into the area of virtual reality. In this case, virtual reality is being tested to assess its viability for reviewing transportation designs, such as automobile tunnels, by simulating the experience of the car driver. Both of these applications are good examples of potential uses of automation for construction which leverage electronic data generated during the design process.

Biography
Mr. Cleveland is president of Jacobus Technology, Inc. in Gaithersburg, Maryland. Jacobus Technology provides consulting services and software products to the Architecture, Engineering and Construction (AEC) industry, specializing in the area of computer-aided design, computer-aided engineering and animation.

Prior to this, Mr. Cleveland was the Manager of Automation Technology for Bechtel Corporation in Gaithersburg, MD. He was responsible for hardware and software procurement, systems operations, networking, user support, software development and computer-aided design activities in the Gaithersburg Regional Office. He supervised the start-up of the group in 1980 and directed the development of Bechtel's 3-D plant design system, 3DM™, and the real-time animation system, Walkthru™. Mr. Cleveland was appointed as a Bechtel Fellow in 1987.

He graduated from Johns Hopkins University in 1972, where he received a Bachelor of Engineering Science degree in Operations Research and Industrial Engineering. He has authored over 25 publications concerning computer-aided design and engineering.

Automation Integration for Construction

Jacobus Technology

Background

- Engineering automation
  - Engineering analysis
  - Computer-aided drafting
  - Computer-aided design and engineering
- Incentives for engineering
  - Reduced cost (fewer hours)
  - Shorter schedules
  - Increased design quality

Background

- Construction automation
  - Construction schedules
  - Status databases
  - Material inventory
- Incentives for construction
  - Reduced field engineering hours
  - Improved materials management
  - More efficient use of field labor

Consequences

- Focus at organizational level only
- Unable to leverage automation efforts of other organizations
- Limits to potential benefits
- Total constructed cost not addressed

New Uses of Automation

- Schedule animation
- Virtual reality for design evaluation

Schedule Animation

- Background
  - Complex, multi-year construction project
  - Multiple design contractors
  - Multiple construction contractors
  - Logistics during construction critical

Schedule Animation

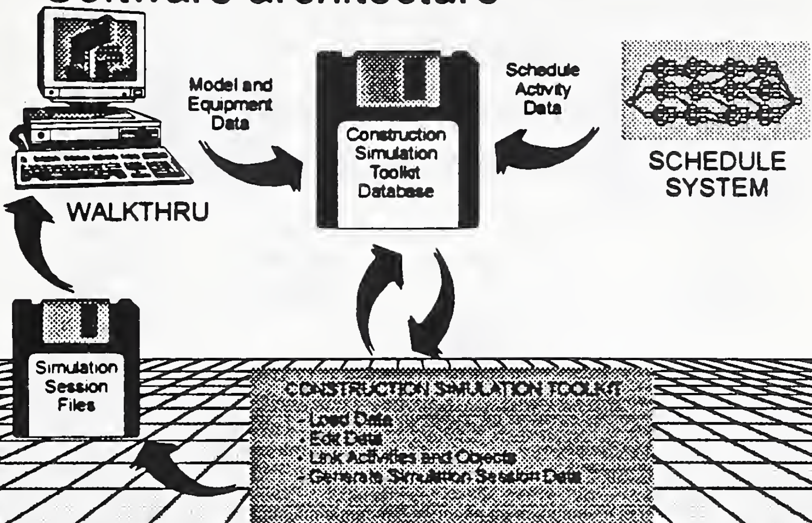
- Solution
  - Develop 3D models from design contractors
  - Integrate design models with schedule data
  - Simulate construction with real-time animation
    - ✓ Construction sequence
    - ✓ Construction simulation

Construction Simulation Toolkit

- Integrates project schedules, 3D models, and real-time animation
- Displays project being 'built' per project construction schedule
- Animates multiple alternatives
- Equipment library for simulation

Construction Simulation Toolkit

- Software architecture



Construction Simulation Toolkit

- Benefits
  - Detect schedule problems prior to the start of construction
  - Improve communication and ensure consistent interpretations of schedule
  - Quickly evaluate multiple alternatives
  - Improved control via better understanding of planned vs. actual
  - Improved method of documentation

Virtual Reality

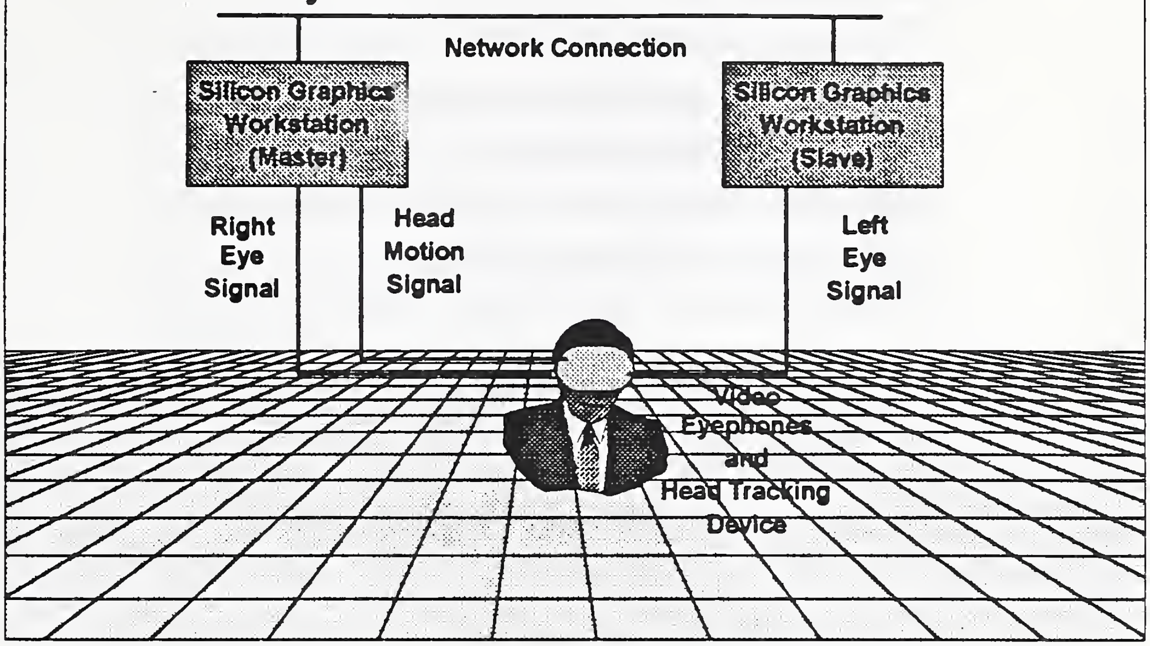
- Background
  - New tunnel alternative
  - Questions regarding drivers' perceptions
  - Unable to evaluate design with current tools

Virtual Reality

- Solution
  - Use existing 3D computer models
  - Simulate driver's path through the tunnel
  - Display image via eyephone headset

Virtual Reality

- Test system architecture



Where is this leading?

- Use of automation will no longer be driven by ***local*** needs, e.g., construction will determine the need for 3D models
- More focus on total constructed cost
- Facility operation is next

What do we need?

- Technologies
  - *Object-oriented systems*
    - ✓ More robust data representations
    - ✓ More flexible systems
  - *More applications for the jobsite*
    - ✓ True construction applications
    - ✓ Designed for the casual user
    - ✓ Integration of design data and site positioning
  - *Standards for integration*

What do we need?

- Cultural changes
  - *Incentives for integration*
    - ✓ Focus on constructed cost
    - ✓ Will require new metrics
  - *Sensitivity to difficulty of changing*
    - ✓ People do act in their best interest
    - ✓ People who seem the most stubborn are usually driven by pragmatism; not ideology

Conclusion

- Computer-integrated construction is a continuous evolutionary process
- Incentives for automating and integrating are dynamic and will change as work processes change
- We must give people an incentive to automate
  - *Tools that work*
  - *Methods for sharing information*

Session #2

Large Scale Robotics

Chaired by:
Kerien Fitzpatrick, Carnegie Mellon University

Participants:

Charles Schaidle, Caterpillar, Inc.

Anthony Stentz, Carnegie Mellon University

William Whittaker, Carnegie Mellon University

James Albus, NIST

Ronald Lumia, NIST

Technologies for Automated Earth-Moving, Spreading, Compacting, Lifting and Positioning of Materials and Structural Elements

Kerien Fitzpatrick
Carnegie Mellon University

Background

Automation is a by-product of progress. As a specific process evolves, its needs become well understood and predictable. This progression toward automation revolutionized the manufacturing world when robotic manipulators and mechanized plants demonstrated what is achievable once the appropriate equipment exists for the task(s) at hand. Productivity boomed, quality increased by orders of magnitude, and costs dropped. Critics argue that manipulators and equipment used in manufacturing are not robotics, but mechanization, and the lessons learned are not applicable to arenas such as road construction, farming, and forestry.

This distinction is not clear since the basic principles and technologies required to automate are the same. Road construction could be considered manufacturing on the move. Its perfect equipment moves over the path, absorbs materials, and lays down a complete roadway of high quality and low cost. The technologies of perception, planning, control, and site integration used in manufacturing are based upon the same algorithms and techniques as those needed for arenas such as road construction. The prime differences between manufacturing and an outdoor task such as road construction include the following.

Structure - Manufacturing is optimized for structure, components come down a certain belt, are modified in some way, and shipped off on another belt. Most equipment performs a single operation. Construction is less structured than manufacturing, but is still presents significant structure. Materials can be unloaded in specific areas to sort by task and designs can be modified to suit automation. All structure existing in manufacturing did not occur naturally, it was created - the same principle can be applied to construction automation.

Mobility - Manufacturing is optimized by fixing the location of equipment while in construction everything is on the move. The difference is construction automation's additional need for position estimation and registration. For example, a bulldozer might be considered a milling machine that moves. All it needs to know is its position, or pose when you consider the many actuators on construction equipment, and have the ability to inform other nearby or cooperative equipment. In past years this goal was unachievable since the accuracy necessary (a couple of inches or less) required very expensive equipment. Cost of recent generations of commercial positioning equipment (lasers and global/satellite positioning systems) capable of achieving the necessary accuracy has dropped significantly. This accurate, reliable, and inexpensive position information will revolutionize the usage of the class of equipment used in highway construction and maintenance.

Multi-Duty - Manufacturing benefits from configurations that minimize the need for equipment to perform multiple tasks. In construction, backhoes and bulldozers perform many different tasks. This does not preclude automation for certain costly or dangerous tasks such as trenching and pipelaying.

Site Integration - While manufacturing benefits from simple communications paths, generally predictable materials delivery, and stable resources, extrapolating the techniques used in this arenas to serve construction is quite viable. Construction projects can benefit significantly by implementing existing techniques with little change. In fact, current construction projects perform planning, scheduling, and resource/materials control, but the difference is that they are more disjoint at certain levels (multi-contractors).

Thus, the technology advancements necessary to make highway construction, maintenance, and operations feasible continue to occur in one form or another in different areas of robotics research. To enable these advancements to benefit FHWA interests, they must be applied to characteristic or archetype tasks to further the understanding required for successful automation. Indeed, some equipment manufacturers have recognized this potential and are investigating certain enhancements such as "intelligent" machinery extending to automated haulage for surface mining. It is in the FHWA interests to guide these developments by directing research into core areas which show the greatest promise of success.

Rationale

To identify which archetype tasks should be more fully explored, the panel evaluated their potential based upon current technology levels, current benefits, long-term benefits, and risk. Four key areas were itemized to represent the basic components of technology relevant to highway construction, maintenance, and operations. These areas include sensing and inspection, large scale robotics, teleoperation and human interface, and integration design, plan, and schedule. Each technology area is then subdivided to even greater detail which are represented in Figure 1a. Construction and maintenance were evaluated as the greatest opportunities for automation. The two flow charts in Figure 2 depict the process through which a project comes to fruition. Central to all tasks are planning and scheduling, indicating that improvements in this area would definitely benefit the FHWA.

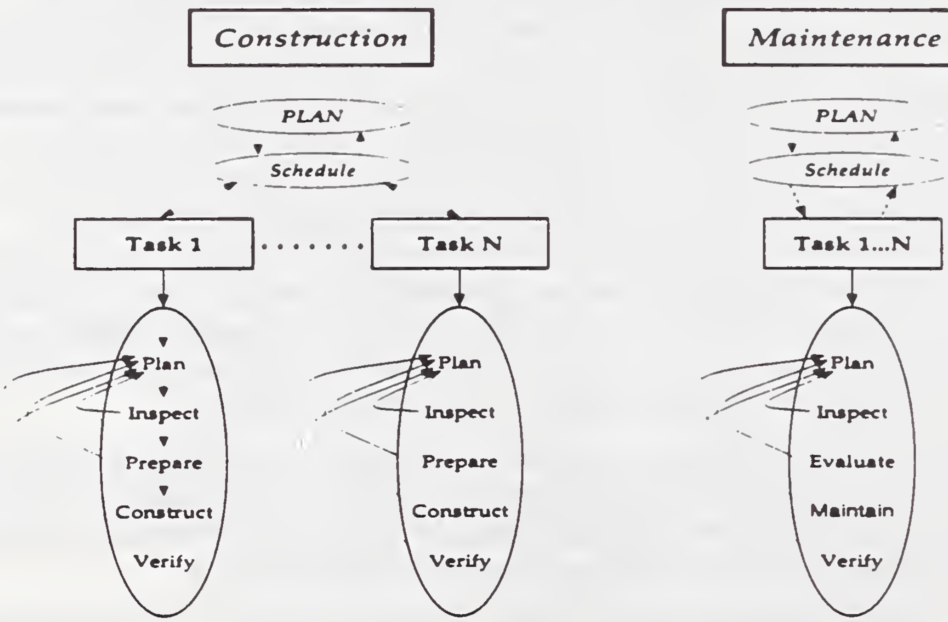


Figure 2

Construction

Construction topics inherently provide an excellent opportunity for automation. Much of this is due to the nature of the project. Construction projects take over a specific area and adapts the area to the needs of the project. Since adaptation is already performed, changes to existing methods would not be as traumatic as implementing an entirely new scheme. The changes for automation could be represented as evolution instead of revolution. Three areas were identified as prime candidates for automation using the criteria listed in the Rationale section - site integration, bridge deck construction, and trenching & pipelaying. Each topic is discussed briefly in the following paragraphs. Greater detail can be found in the proposal sections.

Current methodology separates an overall project into multiple sites, each having a specific site for which they are responsible. Each site has its own plan and schedule within the overall project schedule. A site plan can be further divided into plans and schedules for the individuals tasks required to complete the job. This organization method identifies site integration which includes site design, planning, scheduling as a key focal point. Improvements in site integration provide direct benefits to the contractors involved, the DOTs, and to FHWA. Details of the actual benefits are presented in the first project titled, "Site Integration Through Hierarchical Control." This topic would serve to develop the extensions to ***site integration*** listed in the Background section.

Evaluation of tasks sitting below site integration identified a small number that already exhibited significant structure in the task's environment. Automation projects such as these are less costly and have less risk since the automated method can take advantage of the existing structure. Certain bridge deck designs and construction methods offer an excellent opportunity for automation. The screed, commonly used for bridge deck construction, represents an existing structure which could be modified to perform additional duties beyond the spreading and finishing of concrete. The proposals on automated bridge deck construction and rebar installation provide examples of what is feasible using a modified screed or its support structure. Work of this type precludes the need for position estimation and registration of mobile equipment, as mentioned in the Background section and places emphasis on the advantages of ***structure***.

The last of the construction applications is that of trenching and pipelaying. The primary drivers for this task are safety and efficiency. This area requires additional support due to its ***mobility*** which increases the complexity of automation. However, it is an ideal first step since the process has the equipment move from location to location and the stationary time at each location is sufficient for many cost-effective position estimation and registration methods. This proposed topic also addresses the need to automate ***multi-duty*** equipment such as a backhoe.

Maintenance

Maintenance differs from construction in that the task or project may not be of significant duration, in fact, the duration might even be less than a full shift. While the setup cost for maintenance may not rival that for construction, all DOTs visited agreed that in the future the majority of budgets would be directed towards maintenance. This places additional requirements on automated systems such that their intrusion into the traffic flow be limited. When a maintenance project reaches such proportions that roadways or bridges are shutdown for length periods of time - they resemble more of a construction project and can be treated as such. Using the same criteria as construction, two topics were identified as having significant relevance, near and long term benefits, and minimum risk given existing technology.

The first topic, bridge inspection and maintenance, incorporates ***mobility*** and ***structure*** in the near term with the potential for ***multi-duty*** in future years. Initial versions would most likely take advantage of existing machinery, such as snooper trucks, to minimize the cost. The human bucket would be replaced by custom tooling to handle a specific task. In future years, the snooper-based machinery might be replaced by optimized machinery which would attach to the bridge and would feature a variable toolset. The proposal, "Automating Bridge Inspection and Maintenance" provides further details of how a system would benefit the FHWA.

The second topic, "Pavement Inspection and Repair," focussed on improving the inspection and evaluation process used in highway maintenance. To limit intrusion, this process must occur at highway speeds. This speed requirement places significant emphasis on mobility and structure due to the limited visual presentation offered by the defects. Ideally, detecting defects after they become visual may not suffice in the future and thus the sensing may have to detect them prior to becoming visual. Beyond the actual detection problem, another problem of magnitude must be overcome. Sampling for the small defects for an entire lane at highway speeds also requires improvements in data acquisition modes. The data rate can easily exceed gigabytes per second if filters or compression are not used. The proposed project outlines a method to reduce the magnitude of the data collected and a scheme to overcome the mobility problem.

Earthmoving in the Information Age

C.L.Schaidle
Senior Staff Engineer
Caterpillar Inc.

ABSTRACT: Computers and communications technology have revolutionized many industries. In earthmoving for highway construction,mining and site preparation, this revolution has just begun. The major changes are still to come, but they are just around the corner. This pesentation is a vision of this up-coming revolution in our industry. This vision is comprehensive. It includes basic communication, machine monitoring and diagnostics, job and business management, planning and operations, and machine control. For our industry to realize maximum benefits from the information age, we must have a vision of the future that is shared by technologists, machinery producers, end users, and job planners. Using a highly visual format, this presentation describes such a vision.

THE VISION

- Basic Communications
- Monitoring
- Management
- Planning / Operations
- Control
- Total Information System

KEY TECHNOLOGIES

Existing

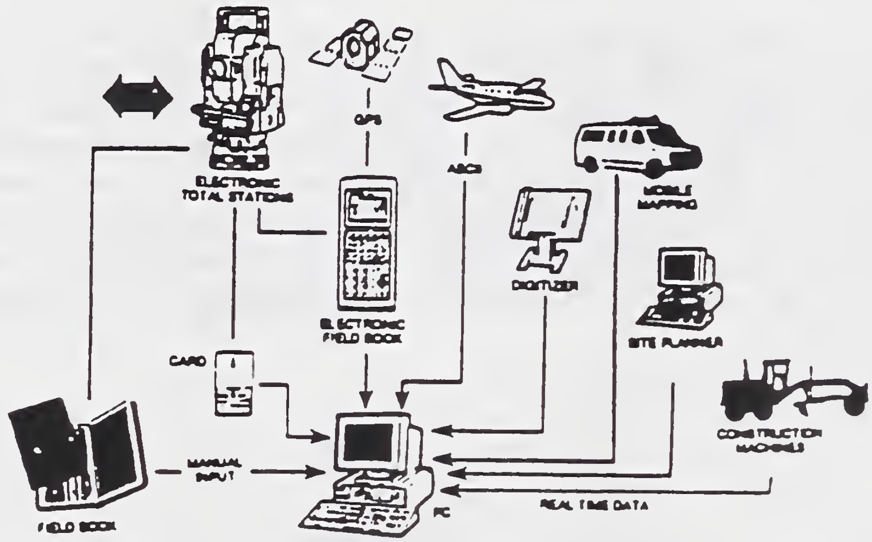
Low Cost. Powerful Computing
Global Communications
Software
Sensors. Actuators. Displays

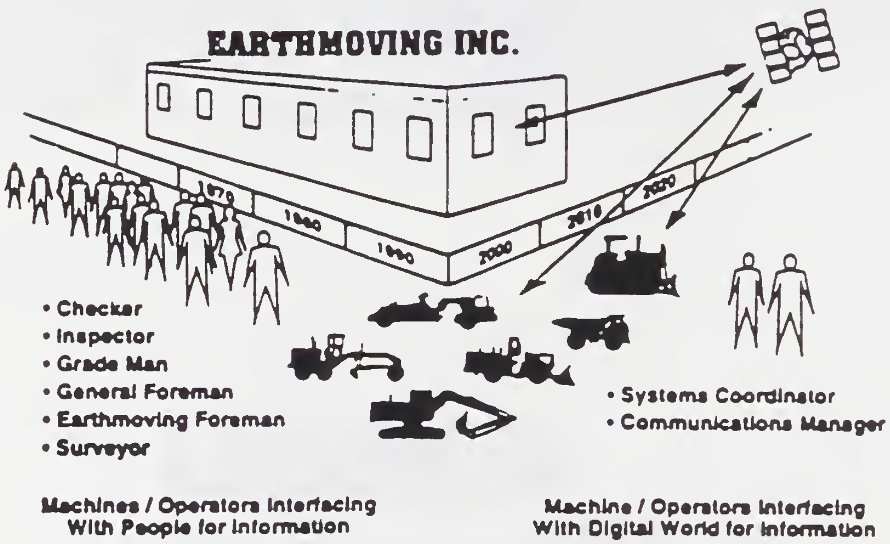
Under Development

Hi Speed. Accurate Locating
Low Cost. Accurate Mapping
Lower Cost Sensor, Actuators, Displays
More Application Specific Software
Systems Integration

Earthmoving in the Information Age

DIGITAL SITE INPUT





KEY CUSTOMER VALUES

Reduced Human Effort
Reduced Material Usage
Improved Job Quality
Better Documentation
Faster Payment
Fewer Mistakes
Higher Machine Utilization

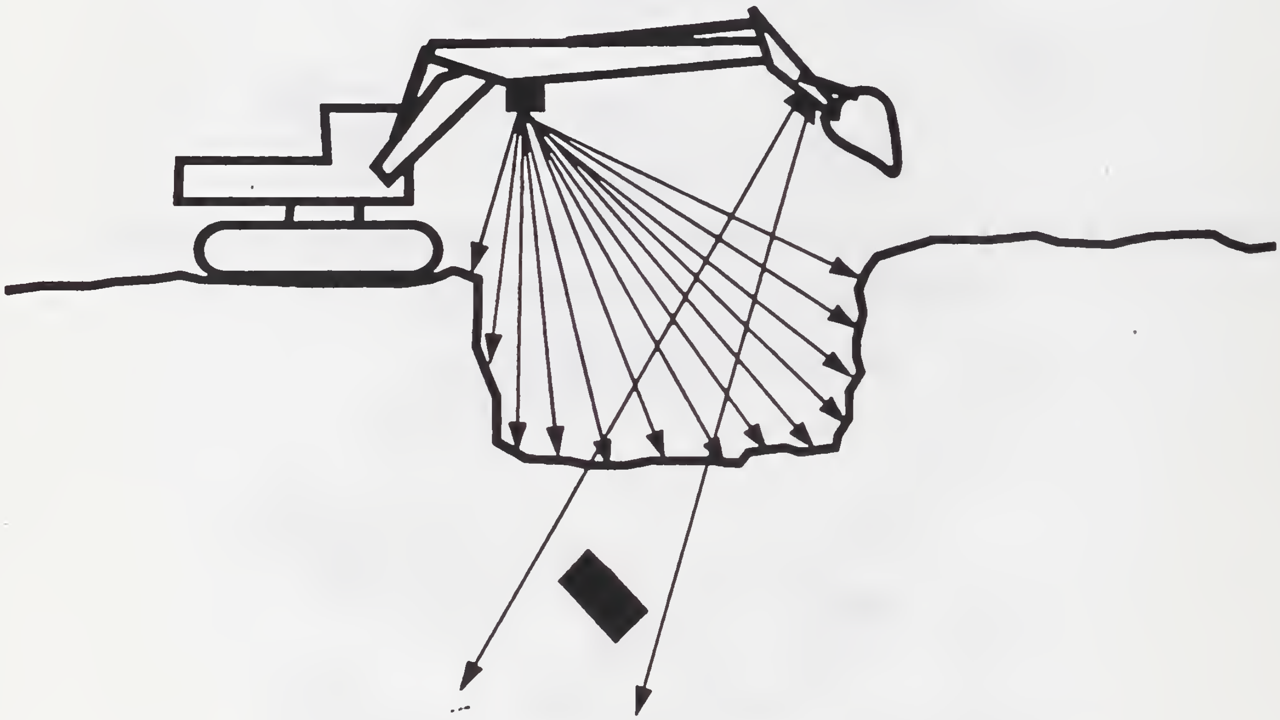
= LOWER COST

Robotic Excavation of Buried Objects

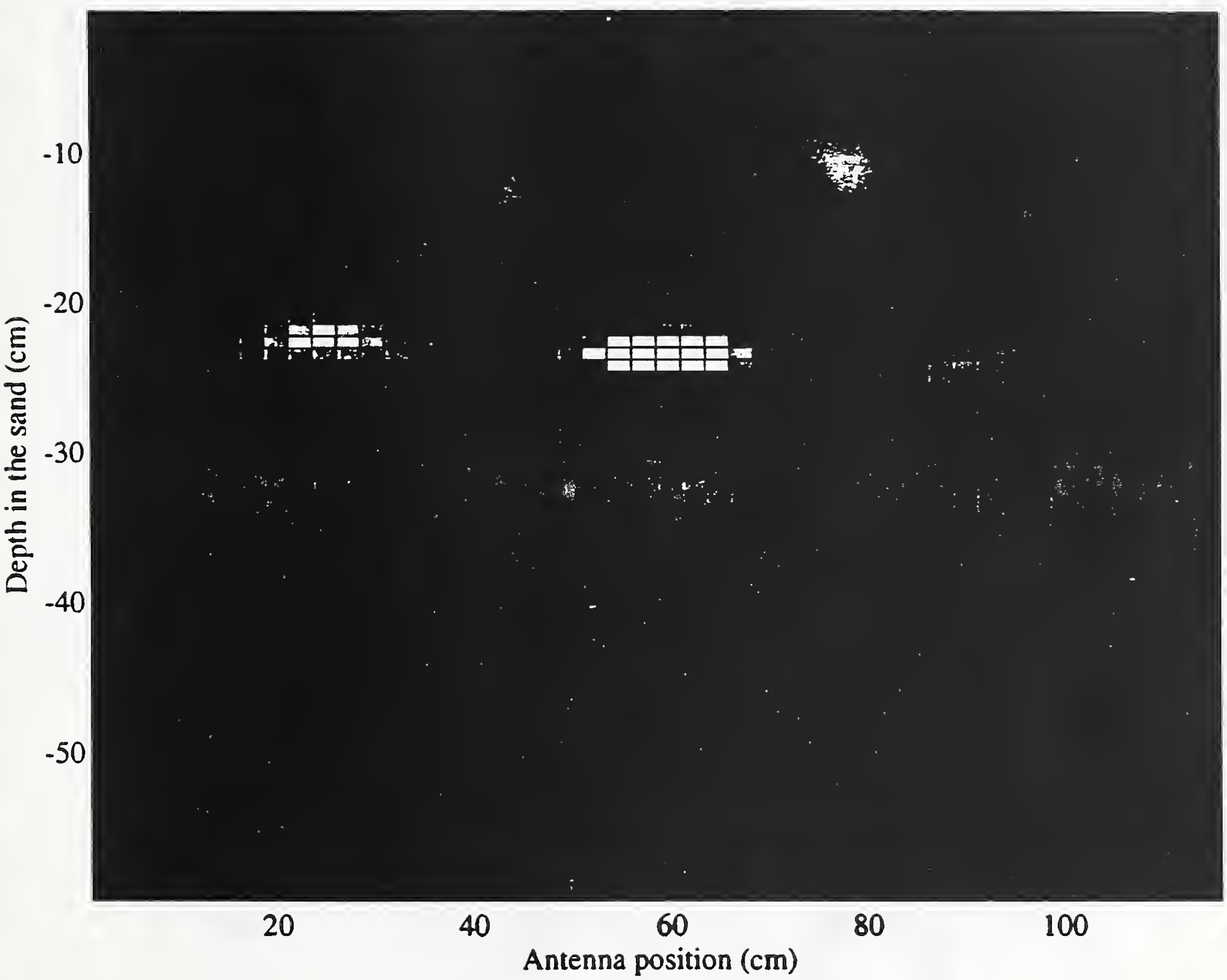
Anthony J. Stentz
Behnam Motazed
Red Whittaker
Carnegie Mellon University

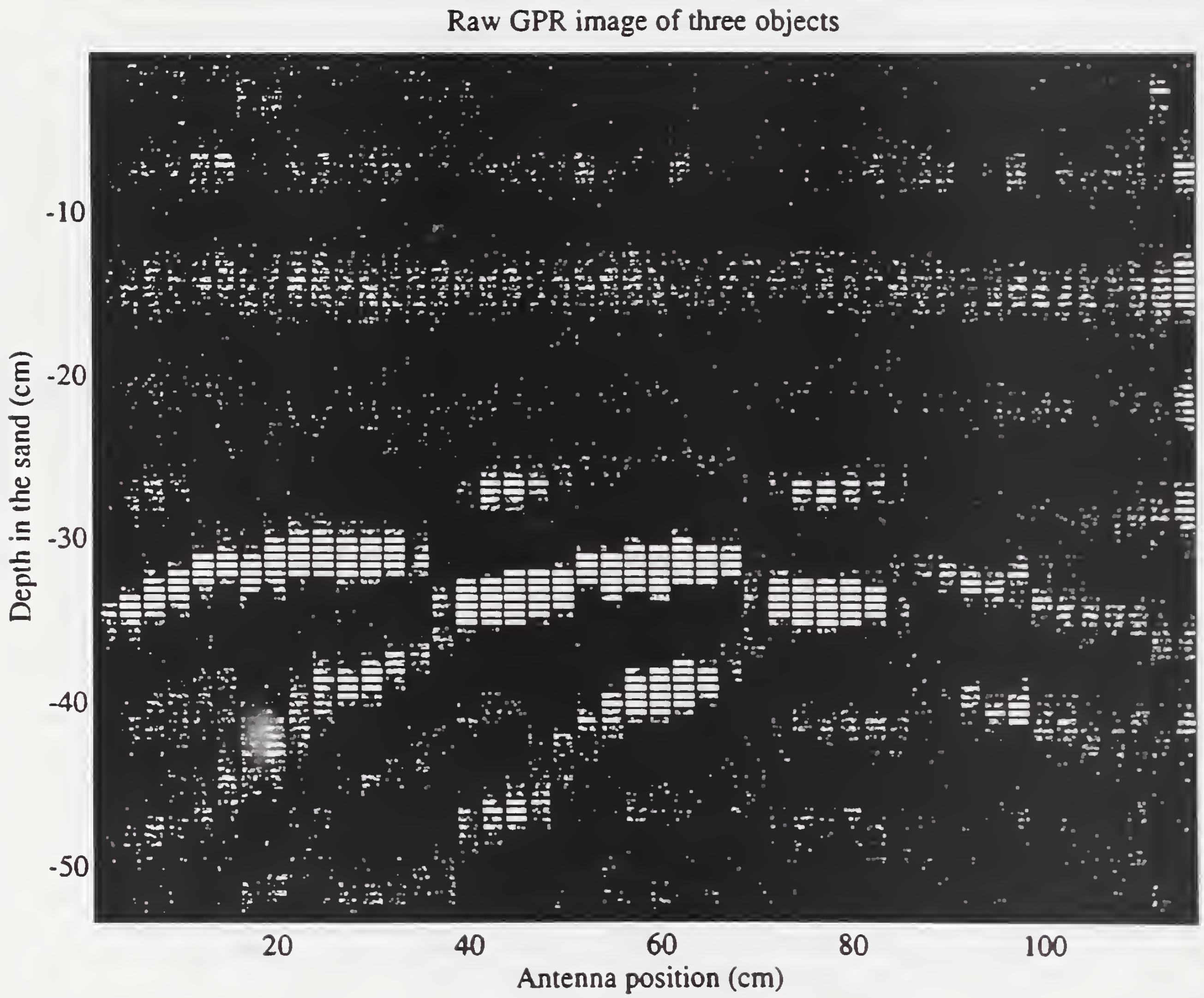
Sponsored by:
Geomechanical, Geotechnical and Geo-Environmental Systems
National Science Foundation
Award No. 9114674

Excavation Scenario

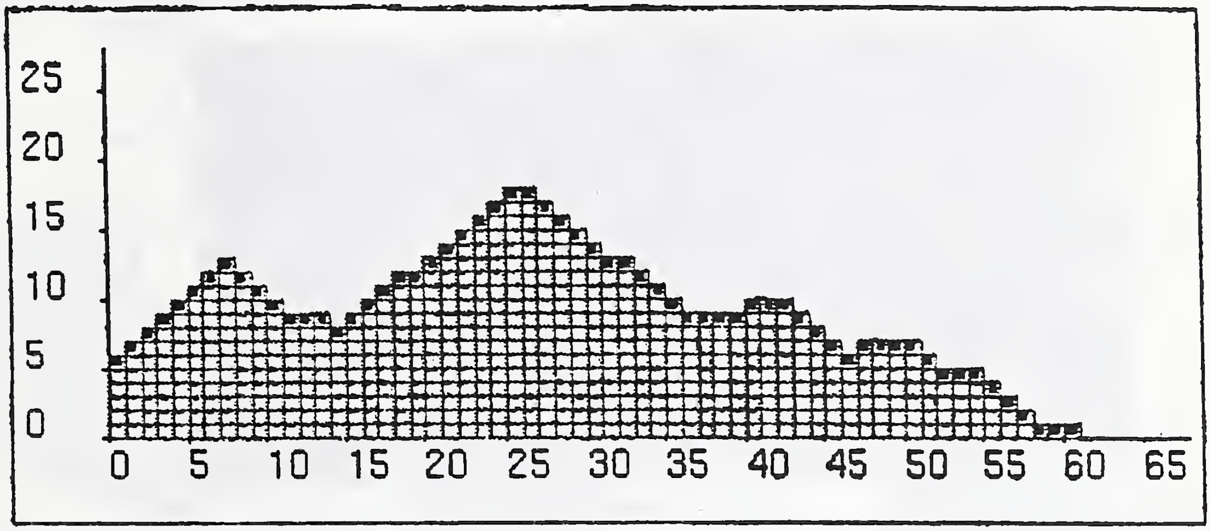


Processed GPR image of three objects

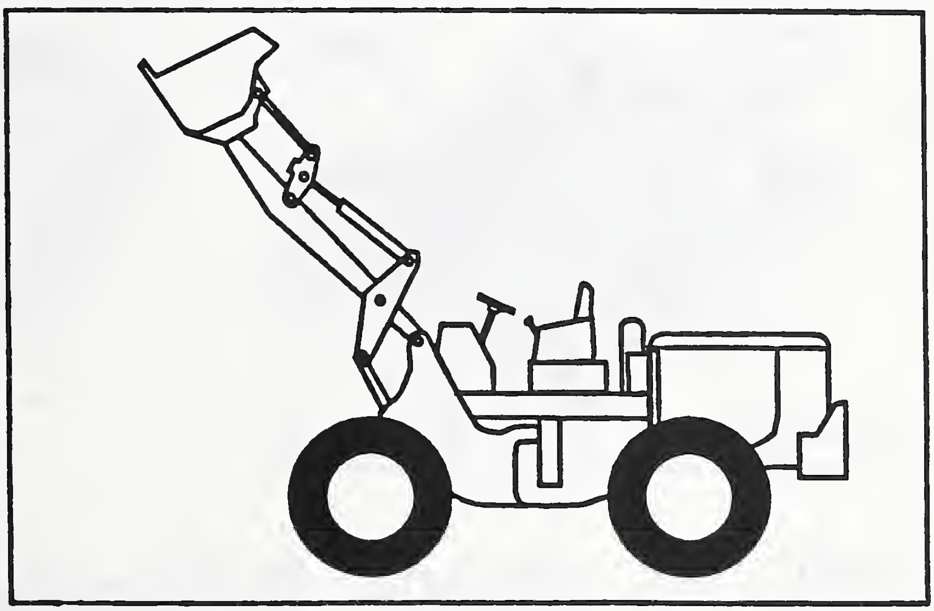



Raw GPR image of three objects
Depth in the sand (cm)
-10
-20
-30
-40
-50
20
40
60
80
100
Antenna position (cm)

An Example

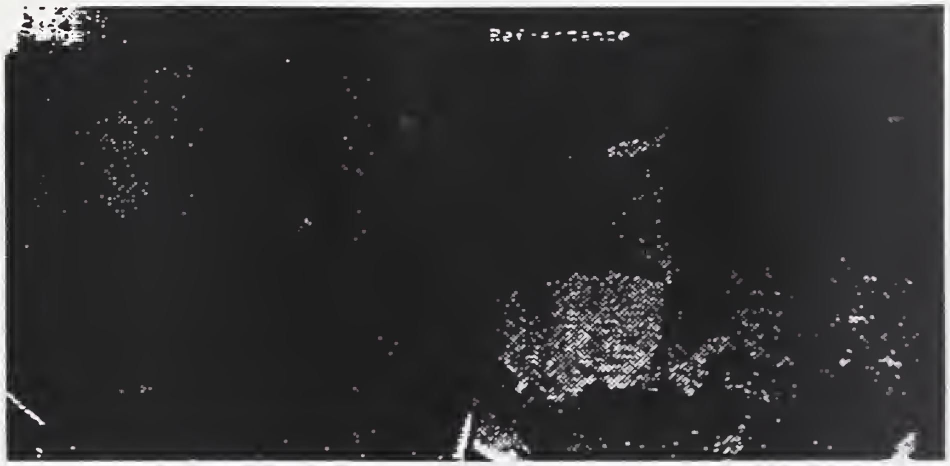


Terrain to be Excavated

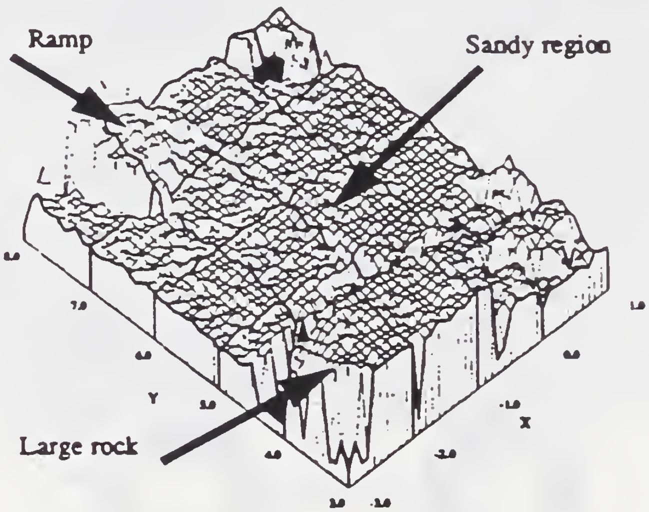


Perception System

INPUT: Sequence of range images from Perceptron laser scanner.



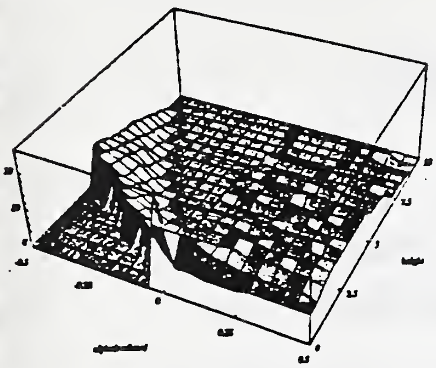
OUTPUT: Terrain elevation maps.



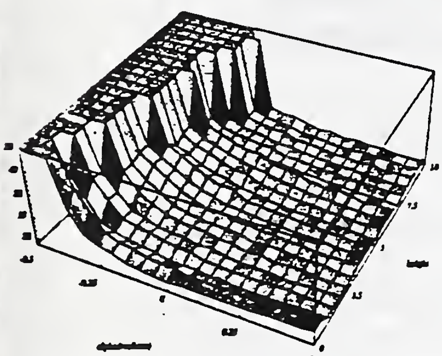
Maps built on demand from other modules (planners *etc.*).

arnegie
ellon

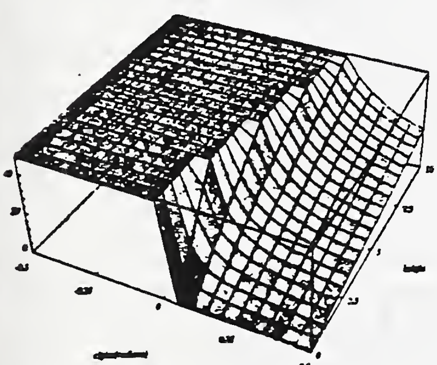
Reachability Constraint(Loader)



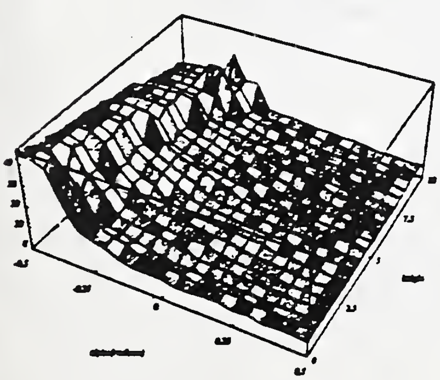
Volume Constraint (Loader)



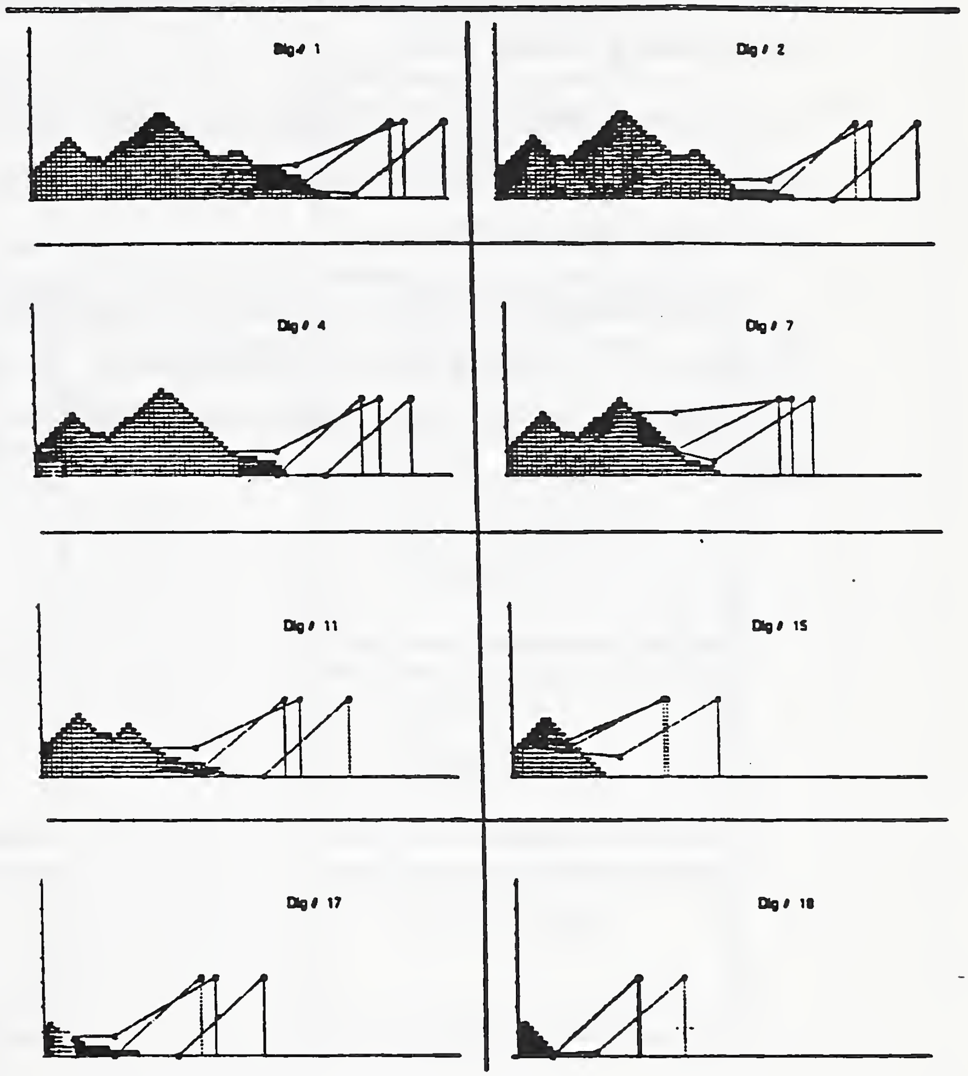
Shaping Constraint (Loader)



Force Constraint (Loader)



Simulation of Loading



Current Accomplishments

- Developed perception software to build elevation maps from laser radar data, fit tool-soil models to force/torque data, and detect and localize small buried objects using ground penetrating radar data.
- Developed planning software to select optimal digging strategy based on initial soil shape, manipulator constraints, and target soil shape.
- Completed an excavation testbed, including Cincinnati Milacron T3 manipulator with bucket, force sensor, ground penetrating radar, laser radar, and sandbox for validating our approaches.

Human-Machine Interface

Control Modes

- Task Control
- Volume Control
- Dig Cycle Control
- End Effector Control
- Direct Joint Control

Display Types

- Labelled Display
- 3-D Subsurface Shape
- 3-D Surface Shape
- Force Feedback
- Live Video

Program Goal and Status

Objective:

- Develop and integrate perception, planning, and manipulation technologies necessary for autonomously detecting, uncovering, and retrieving fragile buried objects.

Applications:

- Space exploration and data sample acquisition
- Characterization and remediation of hazardous waste and unexploded ordnance
- Mining and construction:
    - detection and unearthing of buried pipes
    - debris removal
    - trenching
    - pipe laying

Field Robots for Highway Construction & Maintenance

William L. “ ” Whittaker
Director, Field Robotics Center
Carnegie Mellon University

28 April 1993

Mix of Disciplines

- Planning & Cognition
- Sensing & Perception
- Configuration & Mechanism
- Modelling & Simulation
- Actuation & Control
- Infrastructure & Electronics
- Telemetry & Interfaces
- Software Integration

Field Robots

- Depart from robots for factory and office
  - Significant agenda and resource
  - Operate on environment as it occurs
- Engage the surroundings
  - Sense and Plan
  - Act and React

Perception

- Sensing, Calibration
- Filtering & Feature Extraction
- Modeling & Representation
- Matching & Merging
- Constraint Uncertainty

Planning

- Planning & Prioritization
- Scheduling & Resource Allocation
- Monitoring, Diagnostics & Recovery
- Task Control
- Advising & Learning

Mechatronics

- Configuration
- Dynamics & Physics
- Motion Control
- Devices & Infrastructure
- Telemetry & Communications
- Design & Development
- Real-Time Computing

Future

- Exploit Cross-Over Technologies
- Evolve Prototypes to Products
- Productive Robots in Use
- New Applications & Physical Forms
- Increasing Competence & Self-Reliance
- Tools for Construction, Maintenance & Inspection

Site Integration through Hierarchical Control

Jim Albus
Ron Lumia

Robot Systems Division
National Institute of Standards and Technology
Gaithersburg, Maryland

Robot Systems Division

SITE INTEGRATION

A construction site is like a symphony orchestra with many different players and different skills.

If all the instruments play their assigned tasks (notes), at the proper time (beat), the result is a beautifully coordinated activity (music).

If the players do the wrong tasks, at the wrong time, confusion results (dissonance).

National Institute of Standards & Technology

SITE INTEGRATION

A plan is like a musical score.

Each player has a part to play.
The parts are synchronized to form harmony.

When the plan is right and is properly carried out,
everything arrives just in time,
at the right place,
in the right amount.

Everything fits properly.
Nothing is lost or late.
Nothing requires rework.
Nothing is damaged or wasted.

SITE INTEGRATION

Unfortunately, a construction site is not exactly a symphony orchestra. It is not even like manufacturing.

Just in time delivery is hard to achieve.
Traffic causes delays.
Things don't always fit.
Tight tolerances are hard to hold in the field.
Construction sites are messy and dirty.
It rains, things get lost and broken.

PROPERTIES OF HIERARCHICAL CONTROL

Limit complexity and span of control

Divide and conquer

Add capabilities incrementally from manual,
to teleoperation (fly-by-wire),
to supervisory control,
with growing autonomy.

There exist merging technologies for
design and system engineering.

EXAMPLES OF HIERARCHICAL CONTROL

Ancient Chinese government (3000 B.C.)

Military

Business and government

Factory control, machine tools, robots

Intelligent control of space robotics, unmanned
ground vehicles, unmanned air vehicles,
undersea vehicles,

INTELLIGENT CONTROL ARCHITECTURES

Blackboard - Stanford
SOAR - CMU
Subsumption - CMU
Task Control Architecture - CMU
Pilot's Associate - DARPA
Autonomous Land Vehicle - DARPA
Intelligent Task Automation - AF, DARPA
Real-time Control System (RCS) - NIST
NASREM - NASA/NIST
Meystel - Drexel
Saridis - RPI
U. New Hampshire
RIPE / RIPPLE/GISC - Sandia
Next Generation Controller - AF, NCMS
etc., etc., . . .

AN ARCHITECTURE FOR SITE INTEGRATION

The NIST Real-time Control System (RCS) is a hierarchical control architecture that can integrate many people and machines into a coordinated system.

RCS provides an engineering methodology for designing hierarchical control systems.

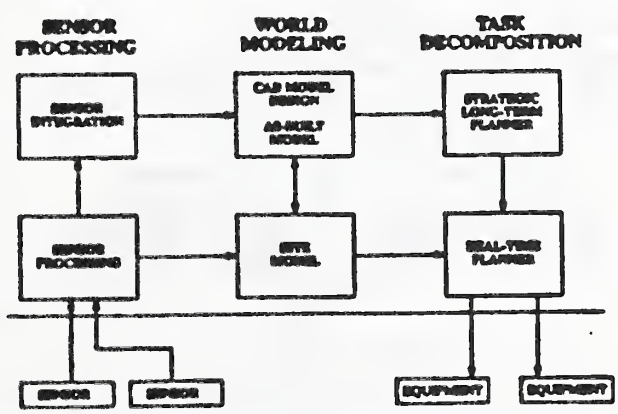
RCS defines how global plans can be decomposed into local actions that can be produced by servo motors, hydraulic flow rates, and engine power profiles.

RCS deals with planning horizons ranging from years and months, down to jobs lasting weeks, days, and hours, and tasks lasting minutes, seconds and milliseconds.

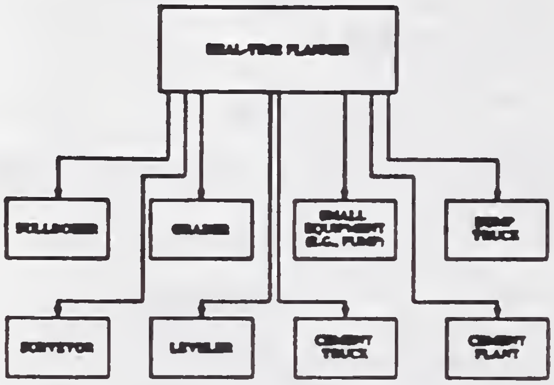
PRIOR APPLICATIONS OF RCS

Vision-guided robot manipulation
Machine tool (un)loading
Workstation control
Robot deburring
Turbine blade chamfering
Composites fabrication
Automated Manufacturing Research Facility
Cell control
Unmanned land and undersea vehicles
Coal mine automation
Submarine operational automation
Space station telerobotic servicer
Next generation controller
Next generation inspection system
Vision-based highway driving
RoboCrane

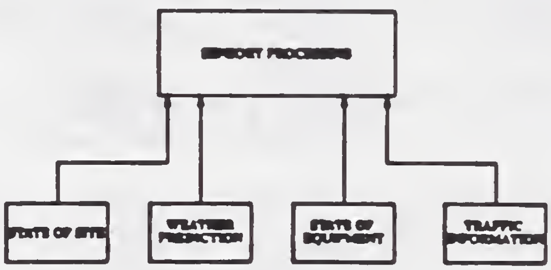
ELEMENTS OF RCS



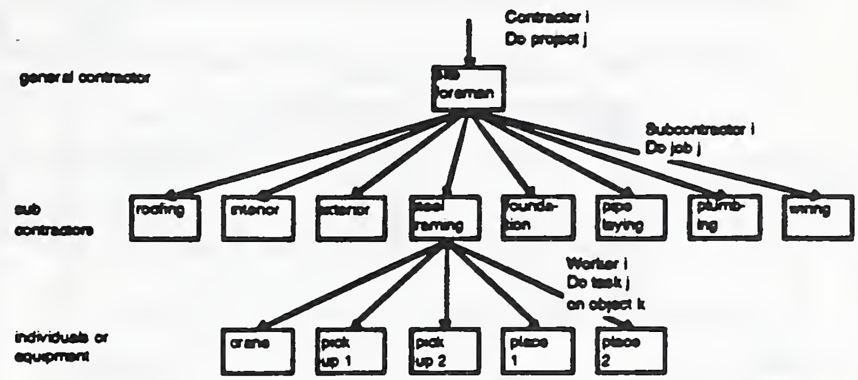
ELEMENTS OF RCS



ELEMENTS OF RCS

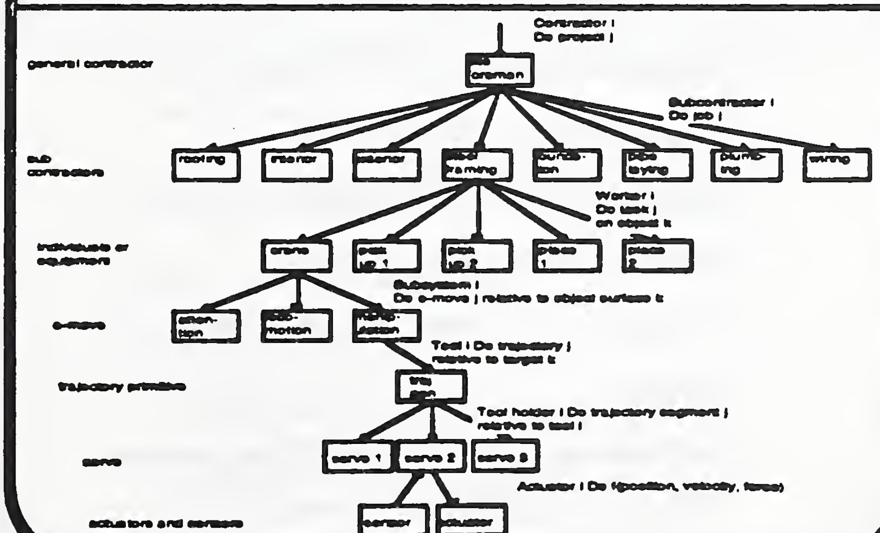


RCS FOR SITE INTEGRATION



Robot Systems Division

RCS FOR SITE INTEGRATION



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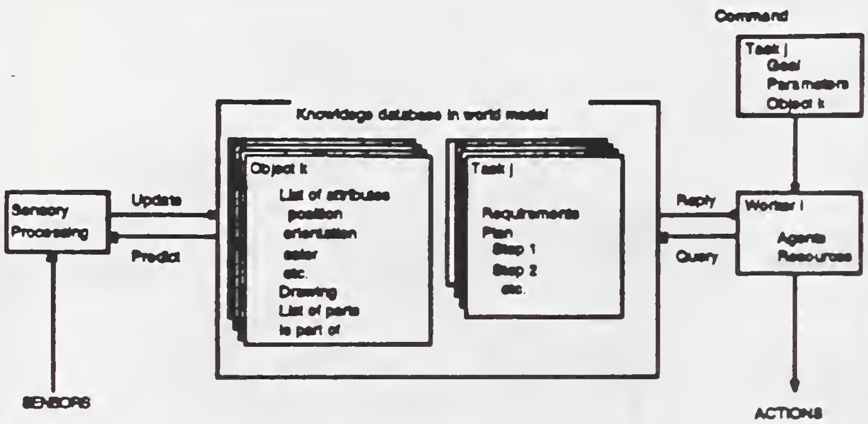
A RCS NODE



SITE METROLOGY

Registration of plans with site landmarks

Excavation and grading to plan

Placement of forms and objects

Positioning of machines and tools

"As-built" vs. "As-designed" database

Cut to fit

Hold tolerances with in-process measurement and feedback control

BENEFITS OF SITE INTEGRATION

Systems can communicate up-to-date information

Sensors can detect errors and variable conditions

Material delivery schedules and equipment use plans can be regenerated in real-time

Operators can have complete information - where, when, how much - with visual displays

Novice operators can produce skilled performance

Measurements can be made (semi)automatically

Required dimensions can be recomputed in real-time for "as-is" conditions

SITE INTEGRATION

Is all this really possible?

At what cost? Is it economically feasible?
Will it save money?

Under what ground rules?

What incentives?

Short term & local
(next quarterly report, individual firm)
vs.
Long term & global
(3 - 30 years, national infrastructure)

SITE INTEGRATION

It has not been practical to organize a construction site like a factory -- until now.

Computer and communications revolution

High Performance Computing and Communications (HPCC)

CAD, process planning, expert systems, intelligent control, learning, sensors, sensory perception, distributed databases, knowledge representation, part geometry and attributes, data exchange standards, supervisory control, operator interfaces, virtual reality.

SUGGESTED NEXT STEPS

Pick a construction project

Design and install a site metrology system

Design and implement a communication network and distributed database system

Develop a real-time materials delivery scheduler

Introduce machines with computer-assisted control and advanced operator interfaces

Measure performance and test alternatives

Session #3

Teleoperation and Human Interfaces

Chaired by:

Leonhard Bernold, North Carolina State University

Participants:

Antal Bejczy, Jet Propulsion Laboratory

H. Lee Martin, Telerobotics International, Inc.

H. McIlvaine Parsons, HUMPRO

NSF/NIST/FHWA WORKSHOP

on

"Research Needs in Automated Excavation and Material Handling in The Field"

Session 3: Teleoperation and Human Interfaces

CHAIRPERSON: Leonhard E. Bernold
North Carolina State University

Participants:
Leonhard E. Bernold, Construction Automation and Robotics Laboratory, NCSU
Antal K. Bejczy, Jet Propulsion Laboratory
H. Lee Martin, TeleRobotics International, Inc.
H. McIlvaine Parsons, Human Resources Research Organization (HumRRO)

Technical Description:

Smart tools, adaptive control of heavy manipulators, data sensing and data representation for teleoperated machines, opportunities through "virtual reality", lessons learned from the application of remote manipulation systems in nuclear environments, design aspects for human-machine interfaces.

LOCATION: Gaithersburg, Maryland

DATE: April 28-30, 1993

Teleoperation and Human Interfaces

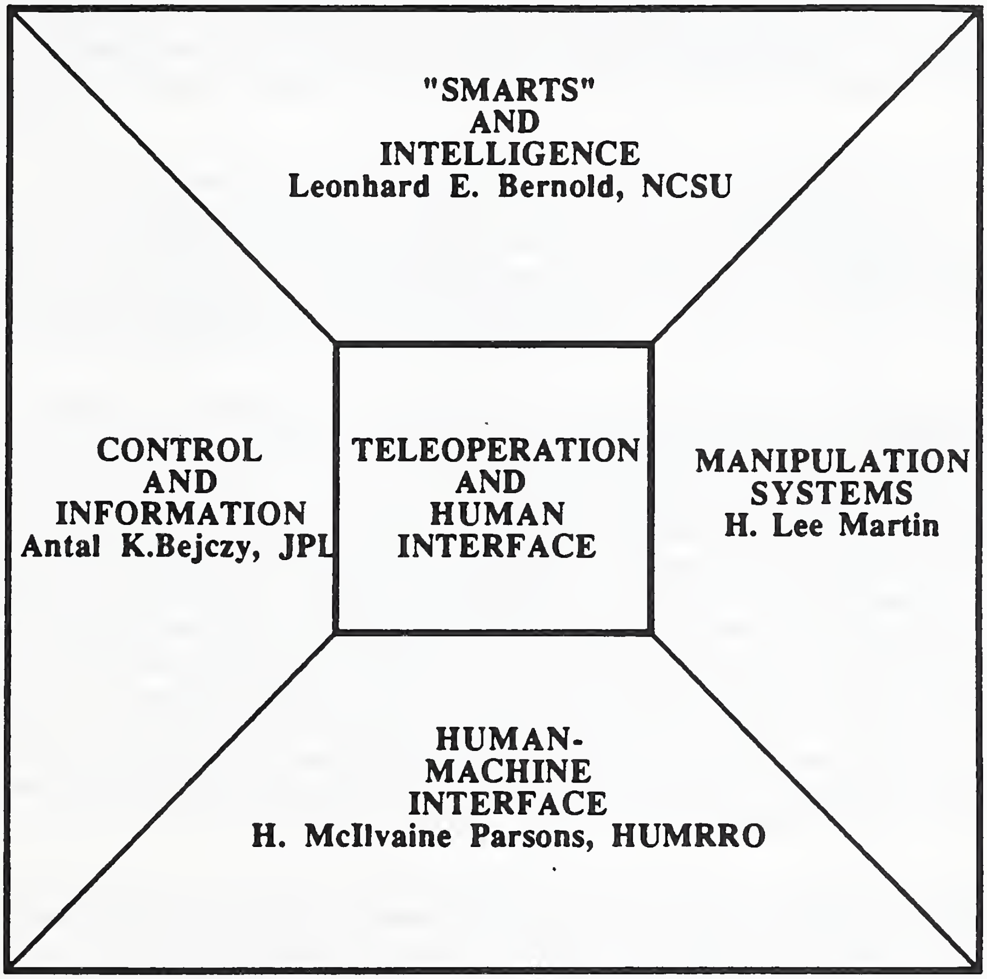
Technical Description:

The development of fully automated and robotic machines for construction has to address many different but interrelated issues. The four main elements include: electronic sensing, intelligent control, human-machine interfaces, and mechanical adaptations. These and many other pieces of this large "puzzle" need to be considered in a "holistic" manner since they are very closely interlinked.

A teleoperated machine is considered a remotely operated system that is controlled by (a) human operator(s) in real-time (or on-line).

This session will address four aspects of teleoperation presented by experts from different industries/backgrounds namely: 1) Smart tools and adaptive control in construction, 2) Large volume manipulation, 3) Control and information issues in teleoperation mode, and 4) Design of human-machine interfaces.

SESSION OVERVIEW



SMART TOOLS AND ADAPTIVE CONTROL FOR CONSTRUCTION,

by

Dr. Leonhard E. Bernold, Director, Construction Automation and Robotics Laboratory, North Carolina State University, Raleigh, NC 27695-7908

Although smart tools don't fit the definition of a teleoperated machine, they represent a category of construction "equipment" that merged some important elements of advanced technologies with traditional (old) technology. For example, a smart nailer increased labor productivity when used by less-skilled laborer. The advantages of this innovative device over traditional nailers stem from the use of an electronic sensor, directly attached to the nailer, which was able to inform the worker real-time when the nailer head was lined up with the (invisible) stud behind the plywood. Thus, nailing accuracy was increased and time for measuring and marking the position of studs was eliminated.

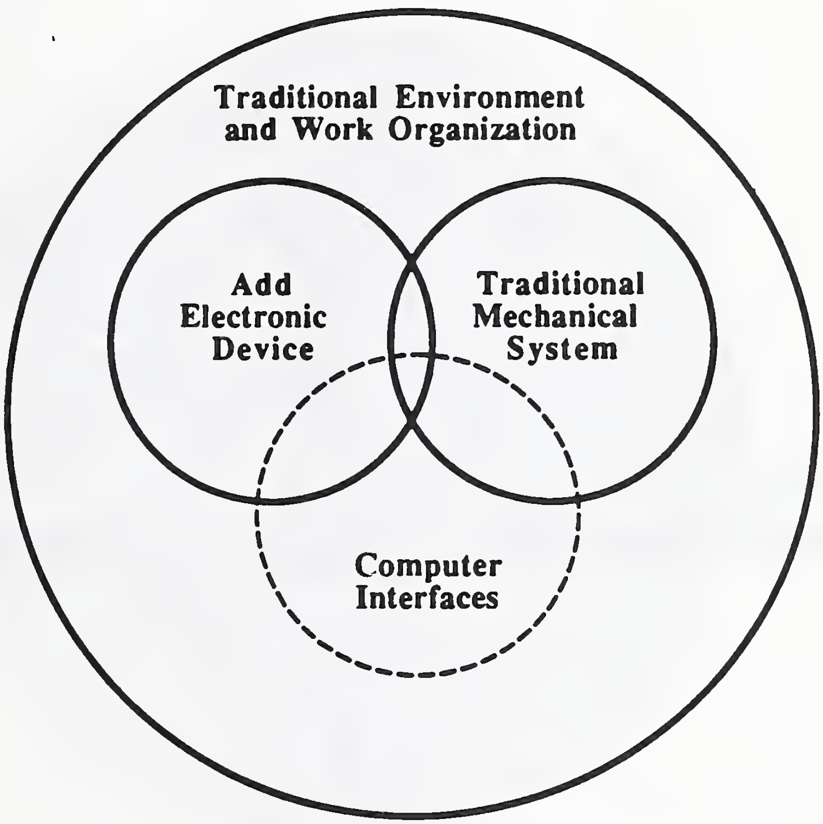
Several aspects of construction operations create great challenges for the development of robust and reliable controls. Some to the important facts are:
1) Construction takes place in a generally unstructured environment, 2) the tasks to be performed require mechanical contact with many non-homogenous materials, and 3) the materials to be manipulated are generally heavy and some important ones chip or break when handled without care (e.g., concrete elements).

Excavation of soil has many characteristics that represent the challenges of construction robotics. It can be considered one of the most unstructured problems in the construction environment. On one hand, many technologies have been developed over history to build shelters using earth. On the other hand, the combinations of encountered soil characteristics are almost infinite and may vary significantly within the range of one meter. While many traditional control strategies developed for applications in manufacturing can not be used for controlling an excavator boom (e.g., position control), a more sophisticated model, depicted adaptive control, has been found useful. An adaptive controller is able to process real-time information about the environment during operation and to adjust (adapt) their behavior to the changing environment. The impedance control model, in particular, stresses the inclusion of the environment into an overall control strategy. It considers the dynamic relationship between the actuator and the environment, such as the soil. Here, the soil is considered an admittance, and the excavator boom as having an impedance which can be modified by the controller.

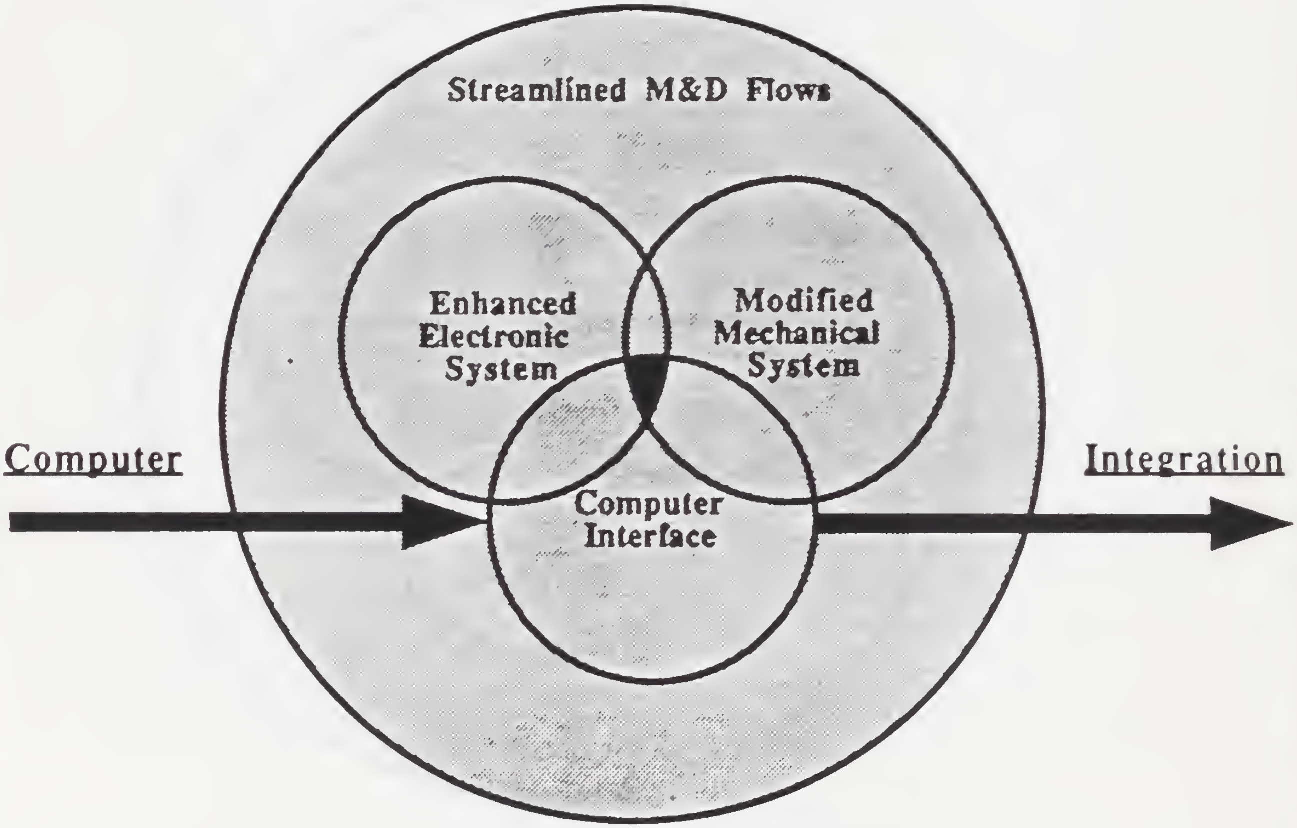
Path planning, which is responsible for identifying the most efficient means to fill the bucket with soil, requires data and information for intelligent decision making. Research in robotic excavation has shown that forces and positions measured during excavation reveal the "grammar" describing the soil conditions much like a cone-penetrometer. The analysis of actual data provided the basis for describing the mechanics of an automatic path optimization system which would be able to adapt automatically to different bucket configurations, task objectives, and soil characteristics.

Adaptive control models have also been tested for other applications such as robotic masonry, and automated rebar bending.

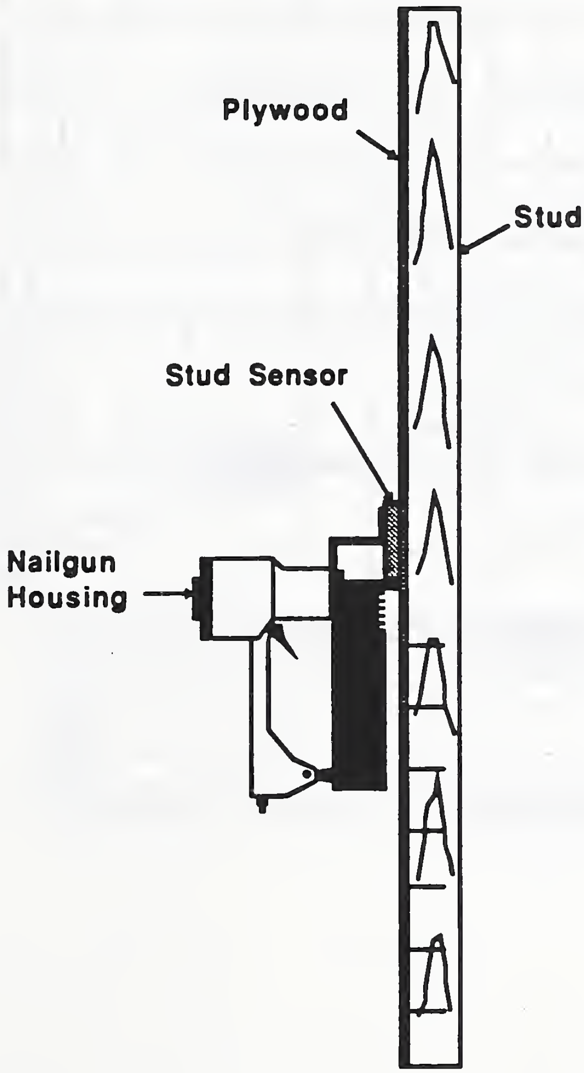
EVOLUTIONARY DEVELOPMENT OF TOOLS AND MACHINES

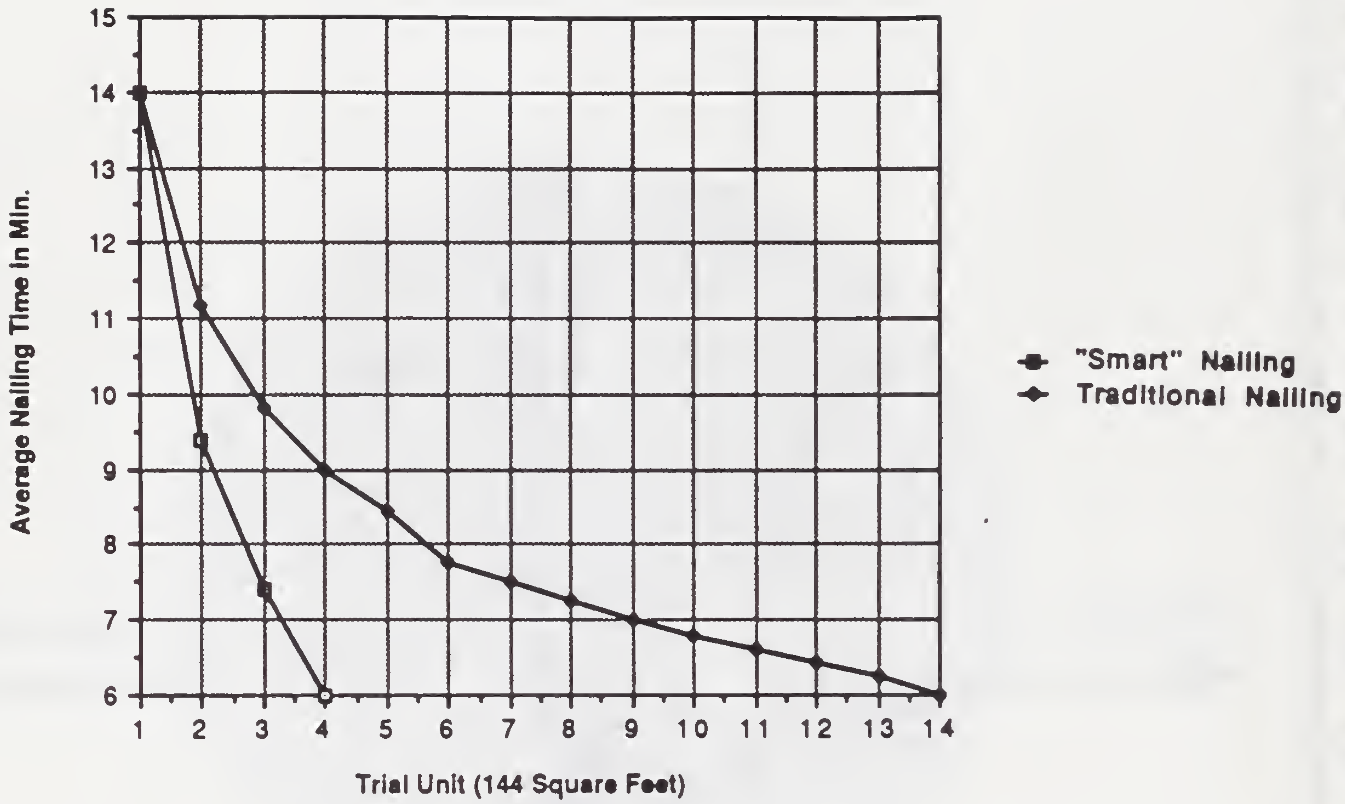


REVOLUTIONARY DEVELOPMENT OF TOOLS AND MACHINES



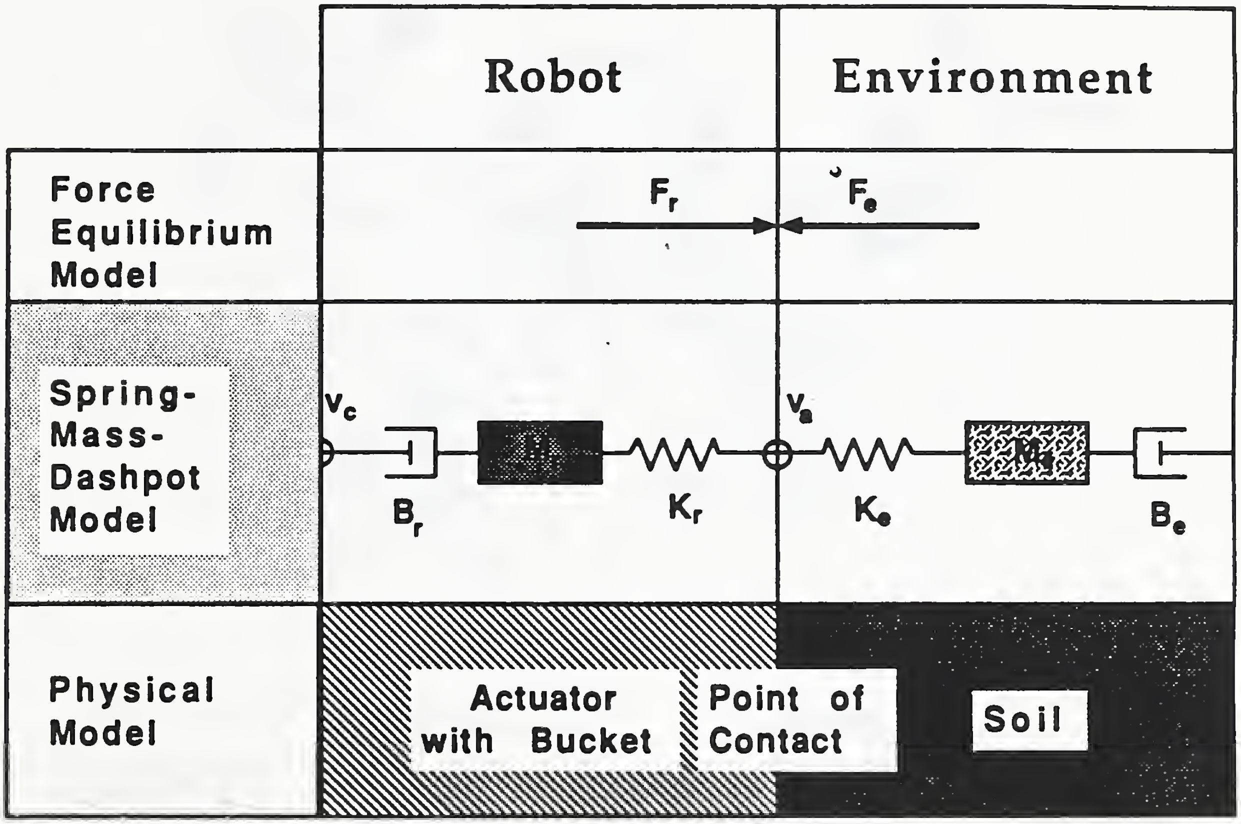
A SMART NAILER



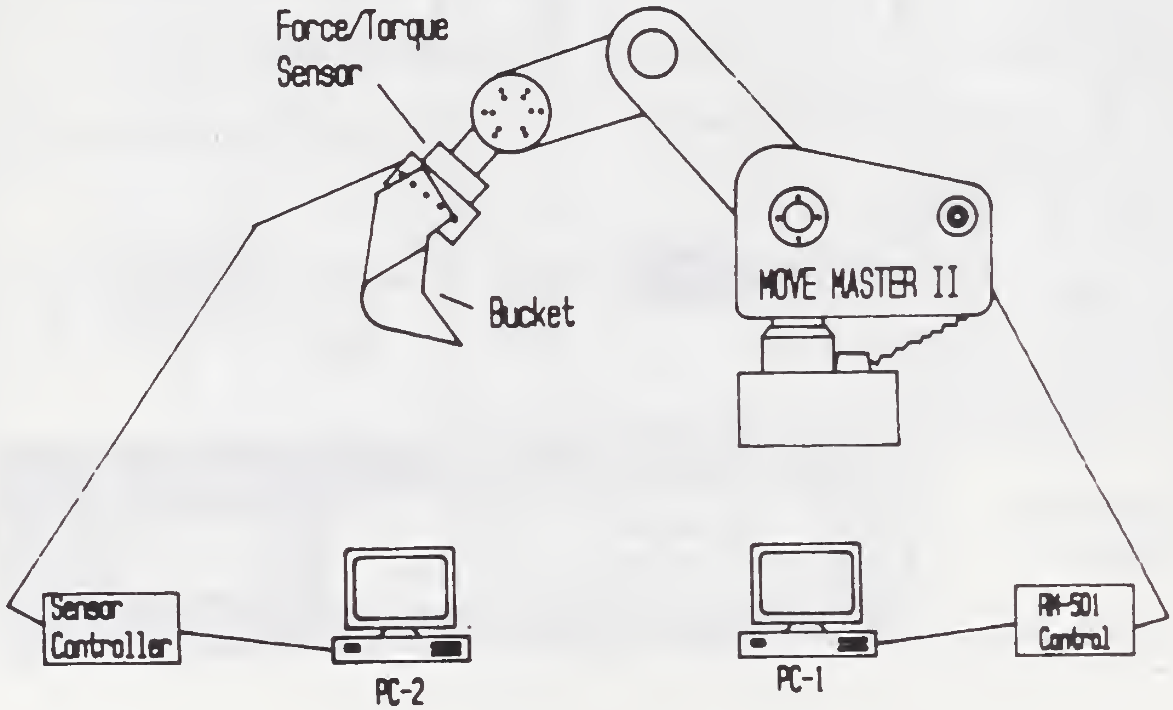


Average Nailing Time in Min.
15
14
13
12
11
10
9
8
7
6
1 2 3 4 5 6 7 8 9 10 11 12 13 14
Trial Unit (144 Square Feet)
"Smart" Nailing
Traditional Nailing

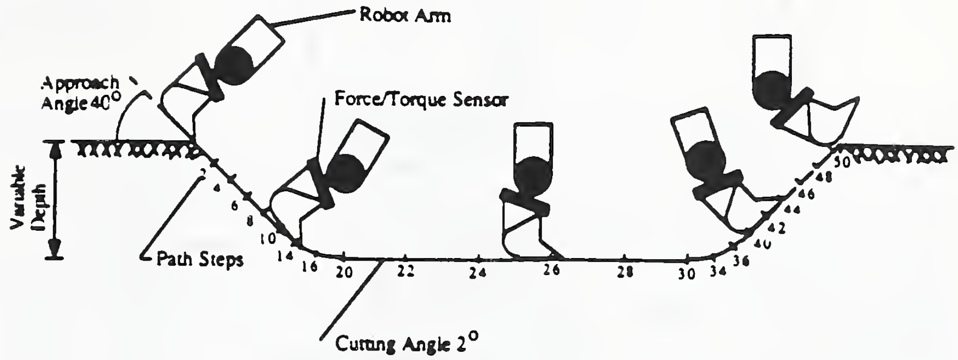
IMPEDANCE CONTROL MODEL

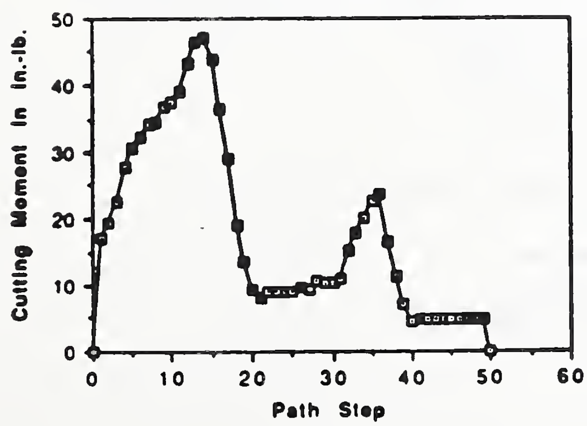


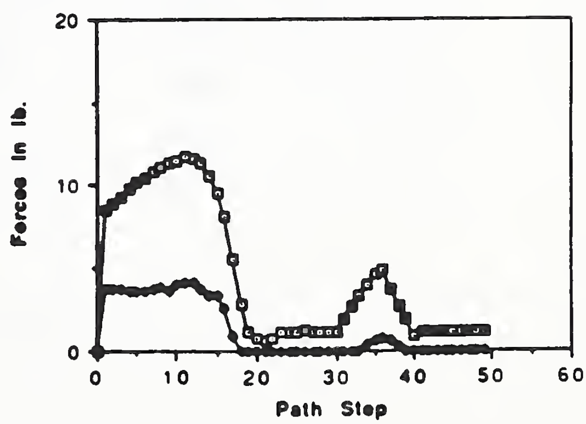
SMALL SCALED EXPERIMENTAL WORK ON PATTERN RECOGNITION FOR "SMART" EXCAVATION

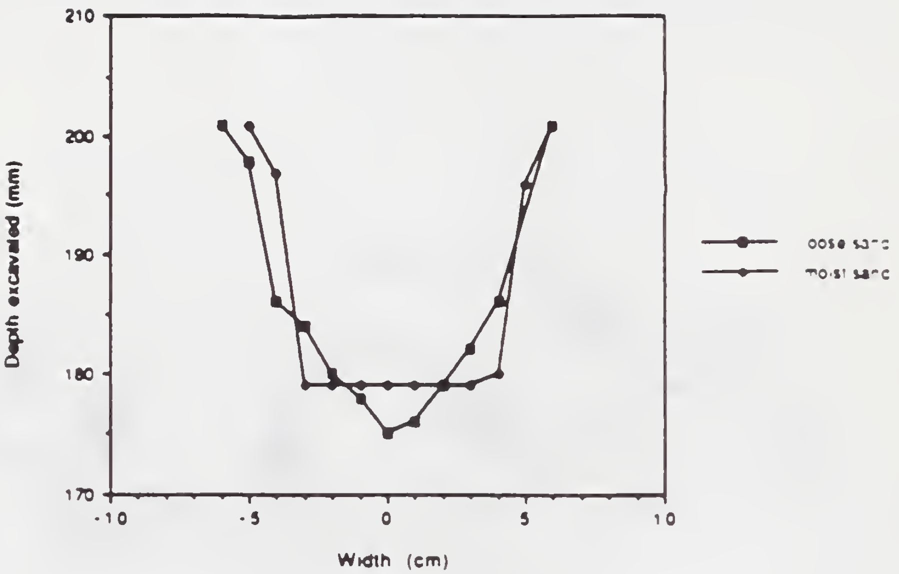


DATA INTERPRETATION WITH PATTERN RECOGNITION

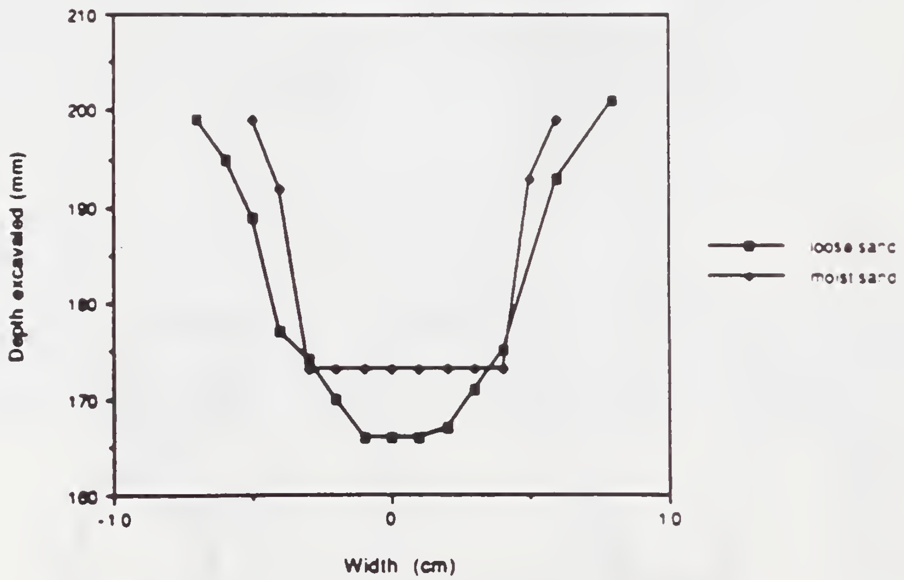




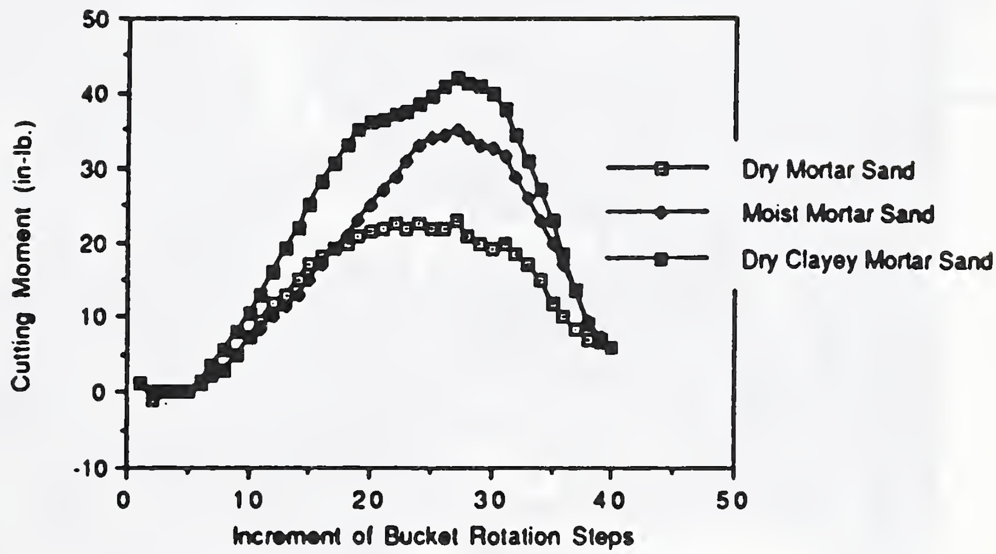




(a) In the first(1st) layer

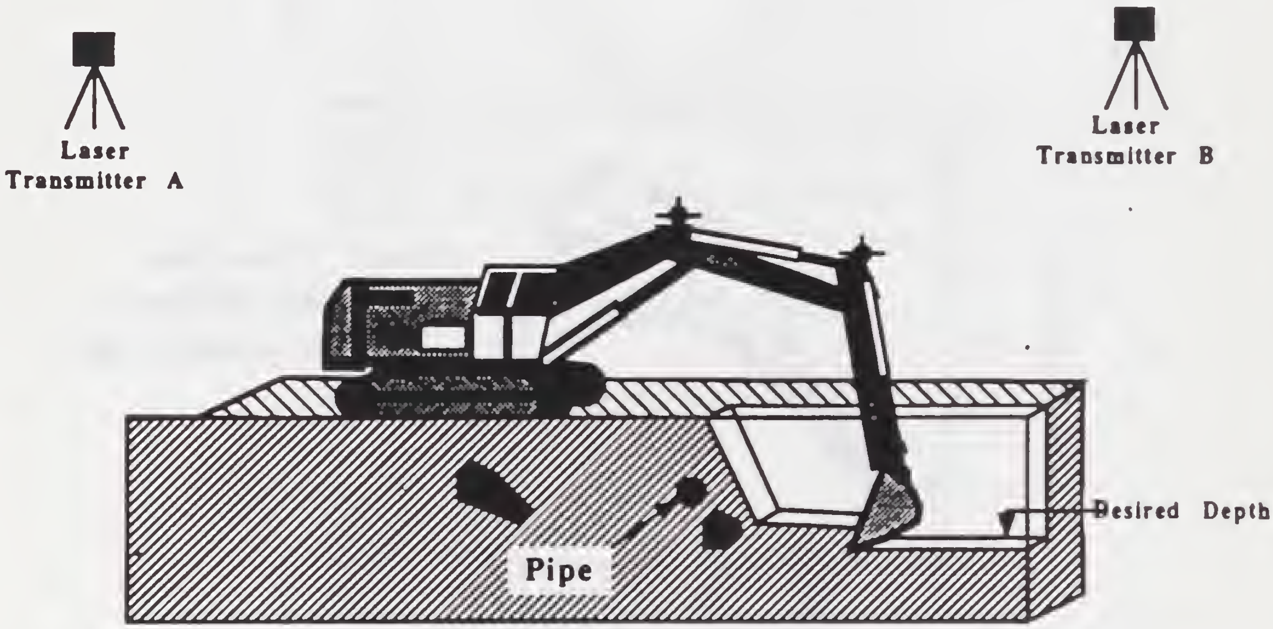


(b) In the third(3rd) layer

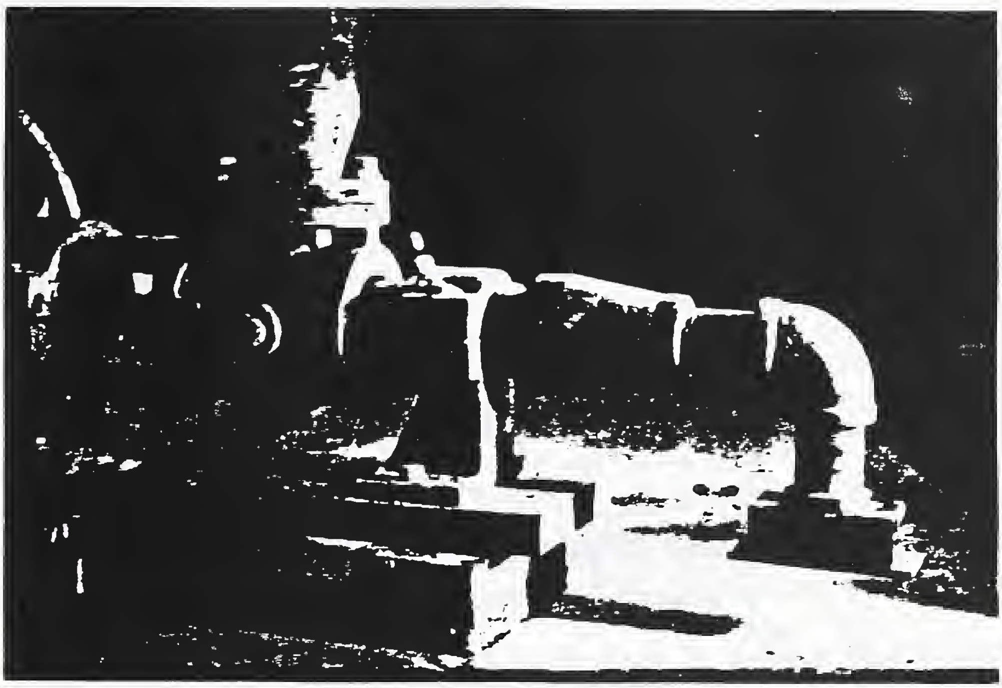


50
40
30
20
10
0
-10
0
10
20
30
40
50
Cutting Moment (in-lb.)
Increment of Bucket Rotation Steps
Dry Mortar Sand
Moist Mortar Sand
Dry Clayey Mortar Sand

ROBOTIC EXCAVATION

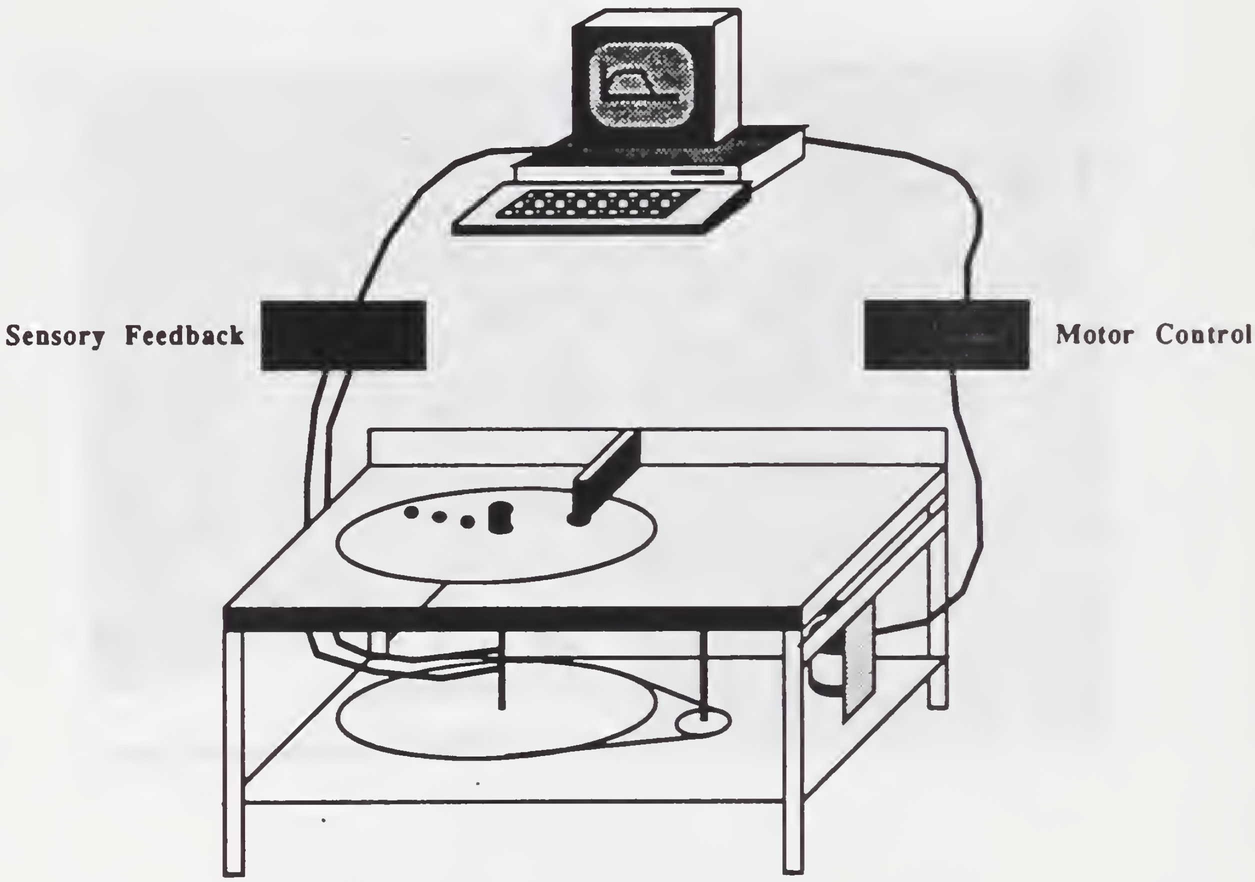


COMPUTER-CONTROLLED MORTAR APPLICATOR



L.E. Bernold, NCSU

AUTOMATION OF REBAR BENDING



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CONTROL AND INFORMATION ISSUES FOR OPERATING LARGE MANIPULATORS AND INTEGRATED EQUIPMENT "WORKCELLS" IN TELEOPERATION MODE

by

Dr. Antal K. Bejczy, Jet Propulsion Laboratory
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The on-line operator interaction with the remote system is a combination of perceptive, cognitive, decision making, and action taking elements. The actions to be taken are typically manual ones. For a successful teleoperated system design and for productive system operation it is imperative to look at the control and information issues not only from the viewpoint of the equipment but also from the viewpoint of the human operators.

The information issues can be grouped into three technical areas: sensing or data acquisition at the work site, data transmission from the remote work site to the control station, and information displays to the operator in the control station. The sensing of the remotely operated machine's internal state is an elementary requirement, and the operator should be aware of the machine's internal state data in the control station. The other sensing domain is the machine's external state relative to the work or work environment. Here, the visual sensors (TV cameras), including their placement and control, play a key role, since remote control to a large extent is a visual perception problem to the operator. Proximity or near-contact sensors can add a necessary supplement to the TV camera information since near-contact events in many cases are not available from TV camera images. Proximity sensors can also add an automatic protective and safety feature to the remotely controlled operation. Another important external state sensing registers the machine's interaction force or torque with the environment. This sensing can also be used to provide a scaled force or torque feedback to the operator's hand through a proper hand-controller device. Sound sensors (microphones) can, in many cases, convey important bits of audible information to the operator's always open and omnidirectional audio channel. The state-of-the-art in the above discussed sensing devices is quite advanced. However, the adaptation of the sensors and their instrumentation to the machine feature and to the work environment may require development efforts.

The sensor data transmission from the remote work site to the control station can present design decision issues: tethered or wireless transmission. Some application cases may permit feasible tethered data transmission. The bulk of the highway application cases, however, may require wireless data transmission. The technology does exist for that, but its adaptation to the application environment will require development work and testing.

A main issue is the way and method by which the information is presented to the operator in a well-organized manner, taking also account of human factors. Today's computer graphics technology offers very useful tools to deal with information organization and display issues in a teleoperator control station. In addition to that, use of today's computer graphics technology permits the creation of a "virtual reality" in the following sense: we can build high-fidelity graphics models of working machines and of objects of interest, and these graphics models can, with high fidelity, be calibrated into a given TV image frame which covers the sight of the machine and objects of interest. After TV camera calibration and object localization, the graphics images of machines and objects of interest can, with high fidelity, be overlaid over the actual images of machines and objects of interest in a given TV camera image frame. This creates a virtual (or phantom) representation of machines and objects in a given working environment as seen by the operator on a TV camera monitor. These types of "virtual reality" graphics displays are very useful tools for planning and previewing controlled actions by controlling the motion of graphics images first before controlling the motion of the real machine. These "virtual reality" displays can also be used for operator training and action monitoring. An interesting property of these calibrated graphics displays is the capability of providing "synthetic TV camera views" to the operator. These views enable the operator to see events which are not visible within a given real TV camera view or to see events for which no real TV camera view is available.

The control issues can be summarized under the three categories: types of control (position, rate, force), modes of control (manual, computer, combined manual and computer), and control system architectures. All three control issue categories have an existing broad technology base, though a varying levels of maturity in the three categories. Therefore, a few remarks are in place here.

Control of large manipulators typically implies the control of not fully rigid but somewhat flexing mechanisms. Computer control typically implies the automation of some manipulator motions or actions. Combined or shared computer (automatic) and manual control typically implies that the operator's manual commands are guided by the operator's visual perception in some motion direction, while at the same time in some other directions automatic computer controls are used referenced to some sensor information. A typical example is an insertion task under visually narrow tolerances, where the forward insertion motion can be manually controlled under the operator's visual guidance, and the lateral displacement and misalignment errors during insertion can be automatically controlled referenced to force-torque sensor data to prevent jamming. If we try to put all these control ingredients together into an actual applied and remotely operated system (large flexing arm, shared manual and sensor referenced computer control), the system may not be fully ready from an operator's viewpoint for actual use. It will need experiments, tests and verification, and operator training.

In conclusion, then, it seems worthy to seriously consider the development of a realistic demonstration system to adjust and verify technology for practical applications, including the experience of the operators in the control station.

LARGE VOLUME MANIPULATION - TECHNOLOGY OPPORTUNITIES AND LESSONS LEARNED FROM THE APPLICATION OF REMOTE MANIPULATION SYSTEMS IN NUCLEAR ENVIRONMENT

by

Dr. H. Lee, President, TeleRobotics International, Inc.

Manipulation of tasks via total or selective autonomy poses significant challenges for the technical and economic implementation in real-world applications. In many forms, the nuclear industry has implemented remote manipulation for maintenance and decommissioning activities. Since construction faces similar challenges (e.g., heavy loads to be manipulated) tested concepts established in the areas of fundamental design, system integration, performance, and reliability related to the successful implementation of manipulation systems in unconstrained environments. In addition, the increased complexity of the tasks provides fosters many emerging technologies for manipulation and sensing.

TRI

Automated Excavation and Field Material Handling:

Teleoperation Lessons Learned

Prepared for NSF/NIST/FHWA Workshop

by

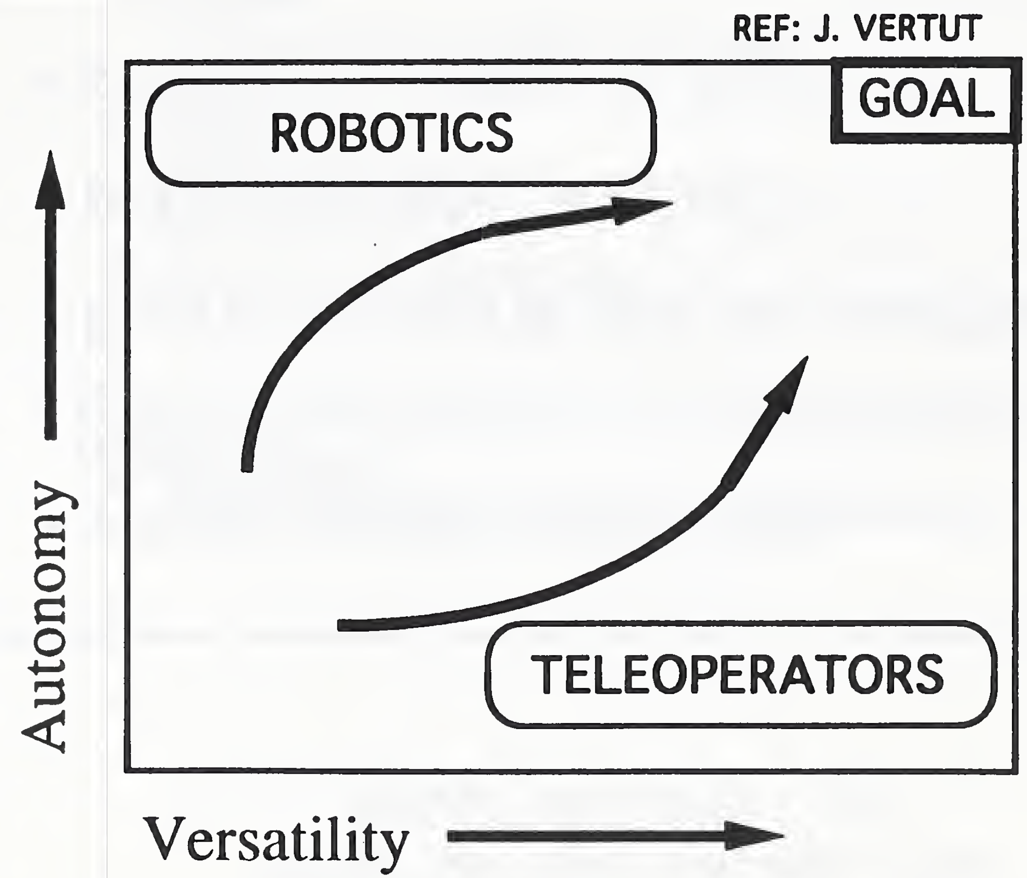
Dr. H. Lee Martin, President
TeleRobotics International, Inc.

TRI

He Who Ignores the Past Recreates It !

- Fundamentals
  - Teleoperation verses Automation
  - Which one? When? Why?
- Some Nuclear Applications
- Personal Observations (lessons learned)
- Transferable Technologies/Sources
- Keys to Success

Teleoperation: Human in the Control Loop
Robotics: Automatic Control



TRI

Different Approaches With Same Ultimate Goal

- Totally flexible, totally autonomous operation !

- Elusive, expensive, near term unobtainable

- Real world decision drivers:
  - Cost
  - Throughput/Size of Task
  - Safety
  - Operating Environment

TRI

Entry Expense is Sizable in Either Case

- Relative advantages of Autonomy
  - Consistency
  - Labor savings
  - Speed of operation

- Relative advantages of Teleoperation
  - Flexibility
  - Environmental adaptation

TRI

Choice of Approach Is Guided by Ultimate Goals

- Environment
  - Less structure --> Teleoperate
- Task Complexity/Diversity
  - More complex --> Teleoperate
- Speed
  - Faster --> Automate
- Safety
  - Eliminate human error -->Automate

50 Years of Nuclear Operations: A Look at Some Systems

- Environment
  - Less structured
  - Variety of tasks
- 0 - person access - no alternatives
- Speed not driver
- Remote handling of nuclear materials

TRI

R&D Should Have Application/Customer in Mind to Retain Relevance

- KISS - Keep It Simple, Stupid!
- Reliability is not an option
- Start small and application focused
- Don't reinvent existing subsystems
- Success: functional results not significant efforts
- Few, if any, easy, inexpensive results

TRI

Strongly Suggest Retrofit of Existing Devices to Rapidly Demonstrate Feasibility

- Caterpillar, Deere, Case, Komatsu invest extensively to deliver reliable platforms
- Teleoperated migrating to Automation
- Goal driven development, incremental & measurable results

TRI

Cross-over Technologies Exist, Key Is Goal Directed Applications

- Case Study: Omniview
  - Goal:
    - Confined Directed Viewing
  - Problems:
    - Volumetric Constraints
    - Complexity of Cabling/Drives
    - Limited response & view field
  - Approach: Eliminate Mechanisms

TRI

Omniview Result: Breakthrough that Will Effect Numerous Viewing Applications

- Approach: Electronic Video Pan and Tilt with Distortion Correction

- Many advantages
  - No moving parts
  - Instantaneous response
  - Multiple simultaneous views from one
  - Simple and compact, no control leads

- Applications
  - Robotics
  - Security
  - Endoscopy

Support Application Driven Research with Clearly Defined Benefits

- Well defined opportunity
  - Labor, safety, or quality the driver?
  - Start simple, continuous improvement
  - Seek a broadly applicable result
  - Leverage existing systems and techniques

- Total automation >> diminishing returns

- Teleoperation defines performance objectives

TRI

Keep It Simple, Savvy!

- Single Minded Focus - (KISS - What)
- Conscious Simplicity - (KISS - How)
- Ultimate Reliability - (KISS - Where)
- Human Augmentation - (KISS - Who)

DESIGN OF HUMAN-MACHINE INTERFACES IN NEW HIGHWAY CONSTRUCTION AND MAINTENANCE EQUIPMENT

by

H. McIlvaine Parsons
Manager, Center for Human Factors, Human Resources Research Organization (HumRRO), Alexandria, Virginia

The following statements focus more on the development as a driver of research than on human factors/ergonomic research itself. A few years ago, in a project for the Army's Human Engineering Laboratory, a survey was conducted to assess design aspects related to human-machine interfaces in remote control centers and test beds for teleoperated vehicles(Parsons, 1989). Though the total of 32 organizations studied was not exhaustive, it showed the extent to which such interfaces were already proliferating; the number today is surely much greater, with mobile teleoperators installed in ground (interior and exterior), underwater, air, and space environments or being planned for these. Problems with operator interface have always existed, however, it is receiving increasing attention from the science and engineering community concerned with robotics and teleoperation.

The above mentioned survey covered the entire range of pertinent design aspects: vehicle and manipulator characteristics, sensors, personnel positions, configuration/layout, reconfigurability and adjustability, control devices (hand-, finger-, foot-, and voice-operated), display elements (CCTV monitors, computer-associated screens, other displays, special displays/inputs to the operator), audio elements, and communications. All of these varied considerably among control centers and test beds, suggesting some uncertainty about what was superior as well as what might need improvement through applied research. Although much development and installation can now proceed with off-the-shelf components, each new system requires systematic study of its particular requirements.

One should also consider the human-machine interface in industrial robotics (Parsons, 1988, 1992). In addition to off-line programming, the principal interface device is a remote control unit called a teach pendant. In on-line programming this controls a manipulator much as though it were being teleoperated. Also for the Army's Human Engineering Laboratory I surveyed the designs of teach pendants used by ten major U.S. and Japanese robot manufacturers. The designs of these have differed so greatly that the Robotic Industries Association, with my participation and help from pendant engineers, and drawing both on my survey and on MilStd 1472C, developed ANSI standard ANSI/RIA R15.02/1-1990 for Industrial Robots and Robot Systems--Hand-Held Robot Control Pendants--Human Engineering Design Criteria.

A study sponsored by the National Institute of Aging investigated how often older people might make mistakes simply in pressing pushbuttons. The error frequencies of most of the 18 participants 65 to 88 years old in an observational study raised some doubts about the feasibility of using teleoperators for household tasks, even if interface designs were optimized.

Design guidelines and simple prototype testing can be helpful in developing human-operator interfaces, along with task analyses, workload analysis, review of end-user characteristics, and study of safety considerations and environmental conditions. Any operational testing of equipment and software should embody human factors components, including representative future operators, maintainers, and programmers.

Indeed, at the start of system development such eventual end-users should be queried methodically about their experience with current equipment, and they should be consulted as the new system is installed.

References:
Parsons, N.M. (1988). Robot programming. In M. Helander (Ed.), Handbook of human-computer interaction. Amsterdam: Elsevier.
Parsons, H.M. (1989). Teleoperator interfaces for remote control centers/test beds. In Proceedings of the Human Factors Society 33rd Annual Meeting. Santa Monica, CA: Human Factors and Ergonomics Society.
Parsons, H.M. (1992). Remote-control units for industrial robots. In M. Rahimi and W. Karwowski (Eds.), Human-robot interaction. London: Taylor & Francis.

Session #4

Automated Sensing and Inspection

Chaired by:

Avi Kak, Purdue University

Participants:

Michael Skolnick, Rensselaer Polytechnic Institute

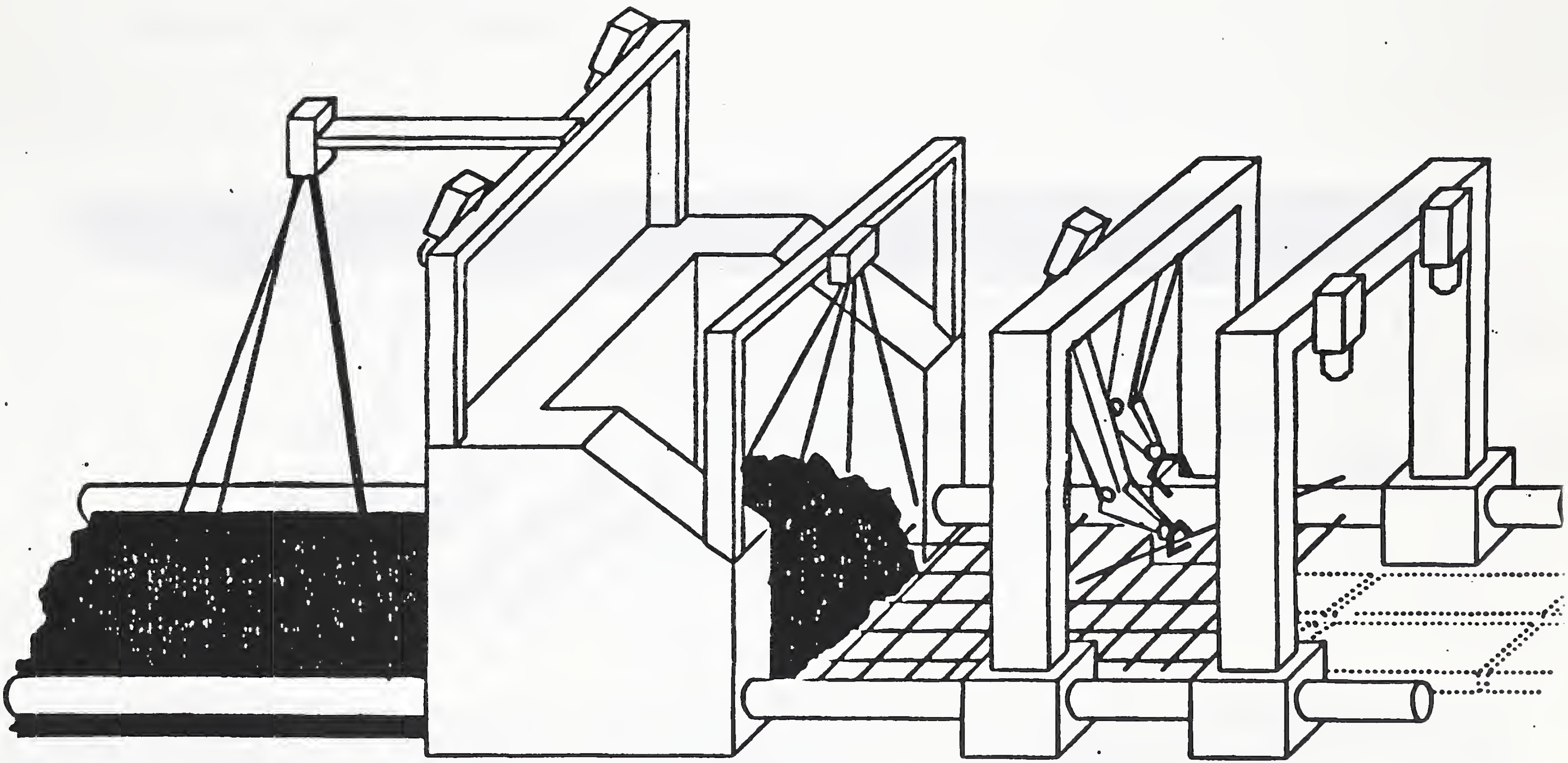
Mohamed Kaseko, University of California

William Herr, Phoenix Scientific, Inc.

Technologies for Inspection of Bridges and Road Surfaces, Automated Surveying, “As Built” Databases, Site Positioning and Quality Assurance

Avi Kak
Purdue University

Concept Drawing for a National Demonstration Project
For the Automation of Bridge Decking



Concept drawing by
R.L. Cromwell
Robot Vision Laboratory, Purdue University

Figure 1

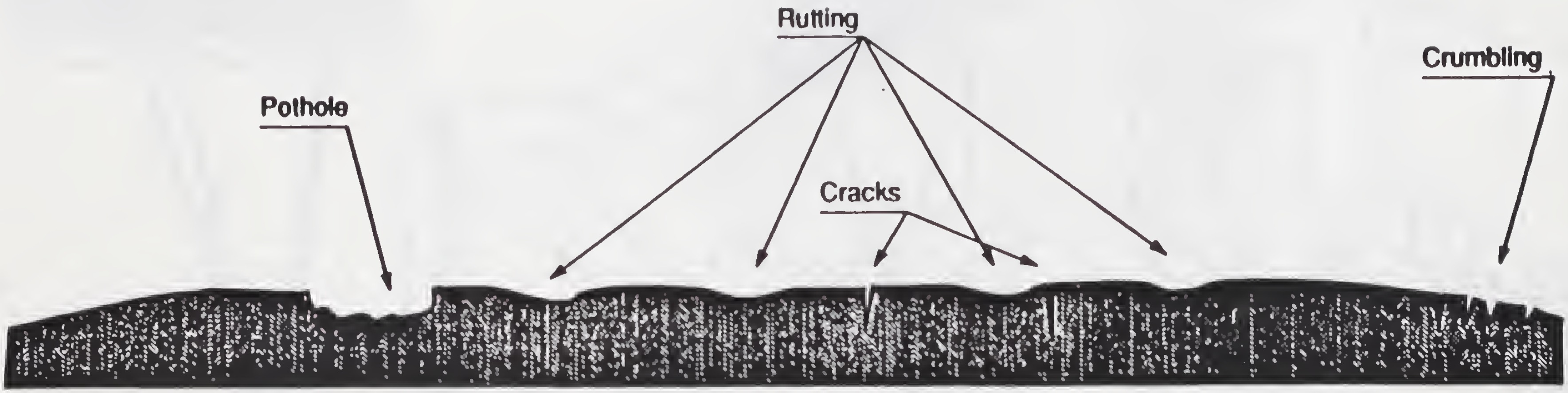


Figure 1

Robot Vision Lab, Purdue University

Rolling-Ball Contact Data Gathering

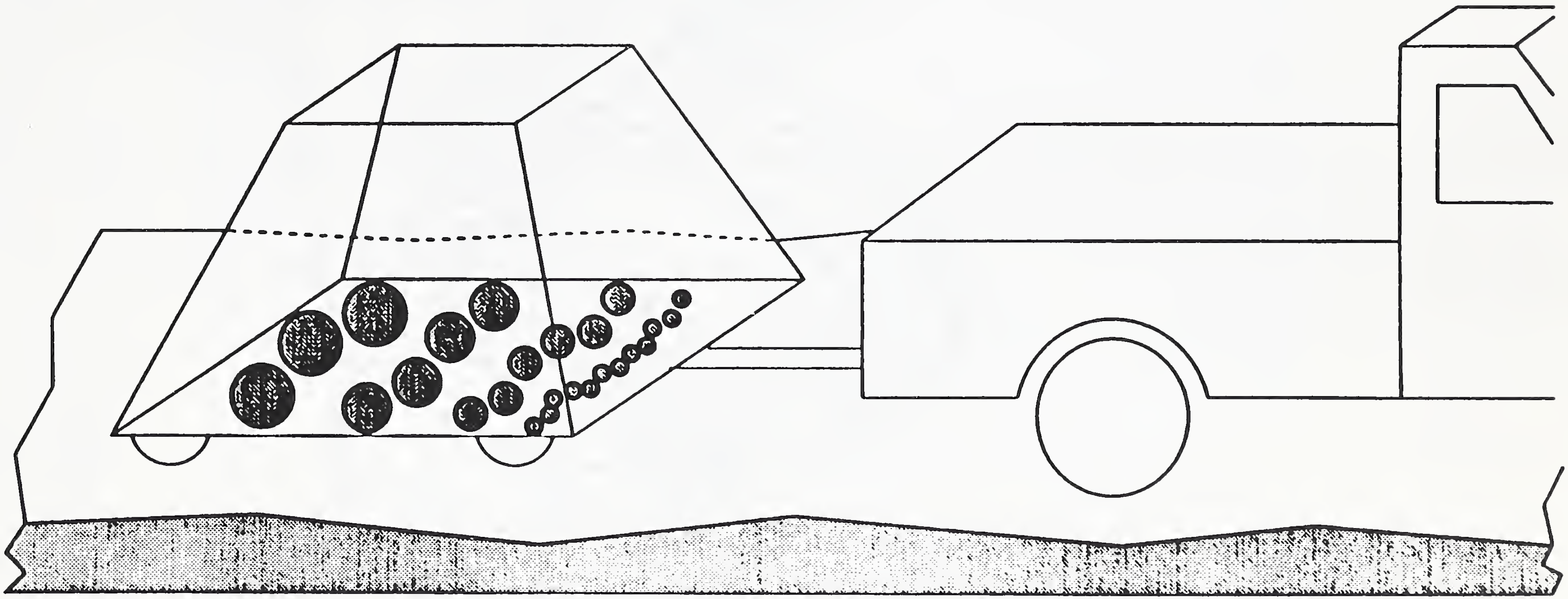


Figure 2

Robot Vision Lab, Purdue University

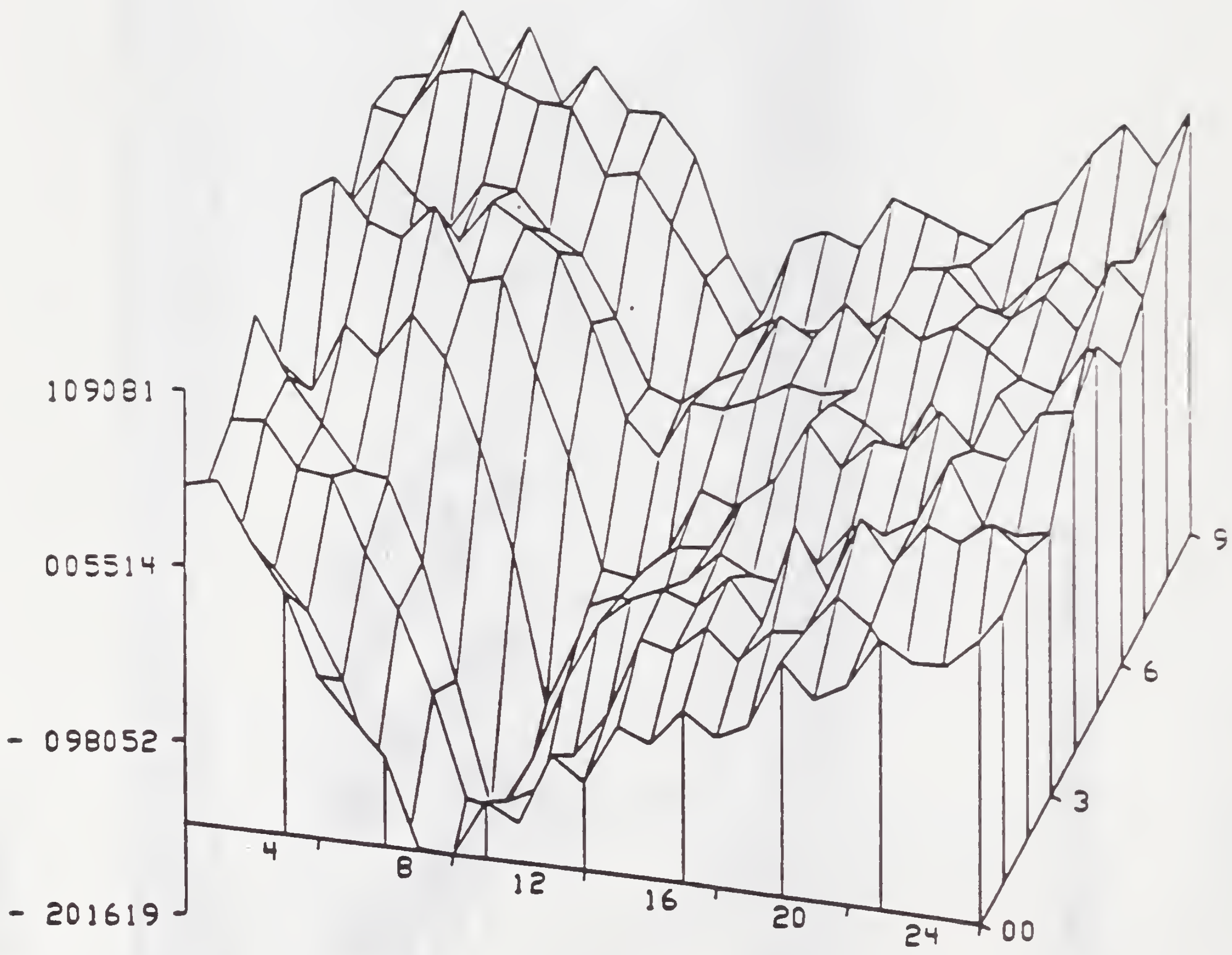


Figure 3

Robot Vision Lab, Purdue University

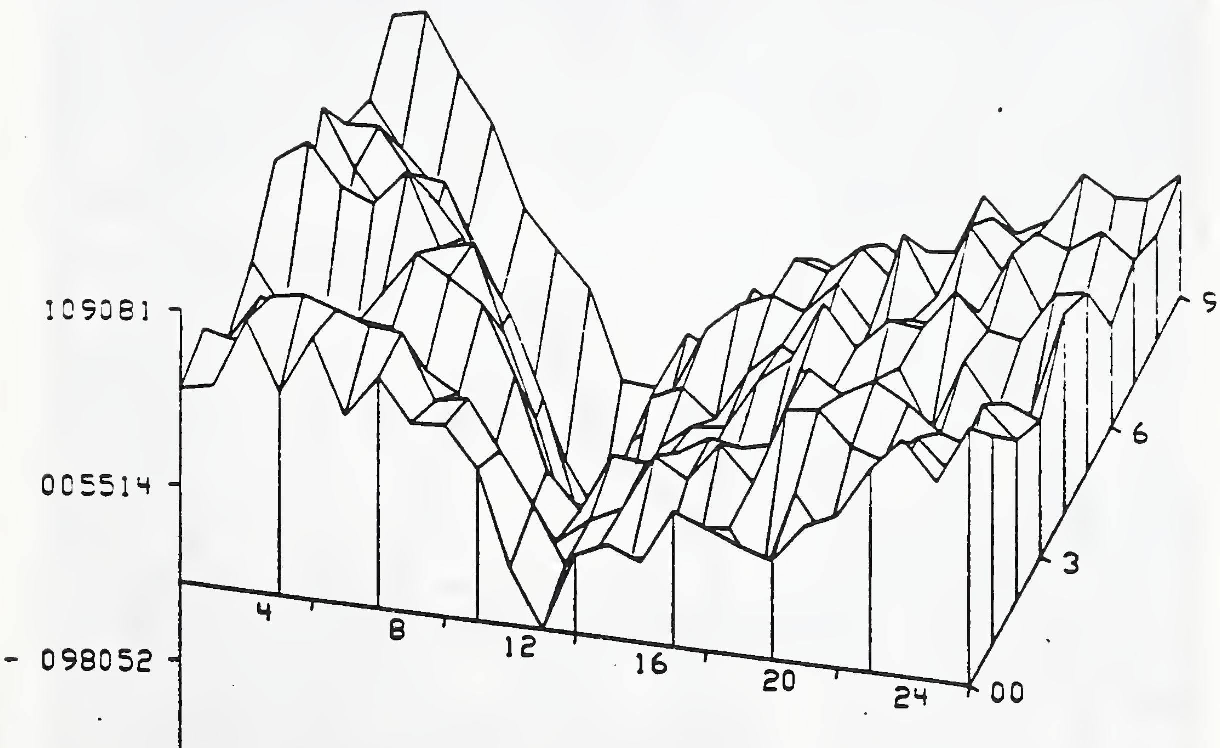


Figure 4

Robot Vision Lab. Purdue University

X-scan Range Data Gathering

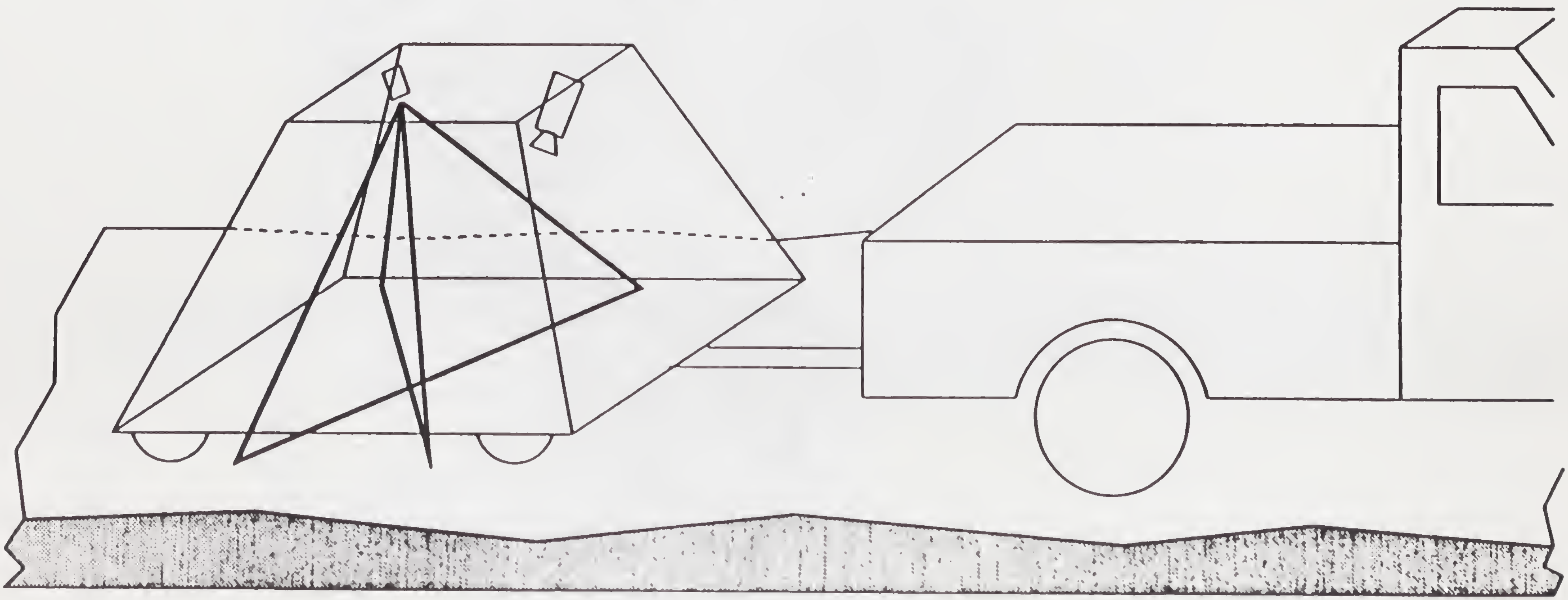


Figure 5

Robot Vision Lab, Purdue University

Z as intensity

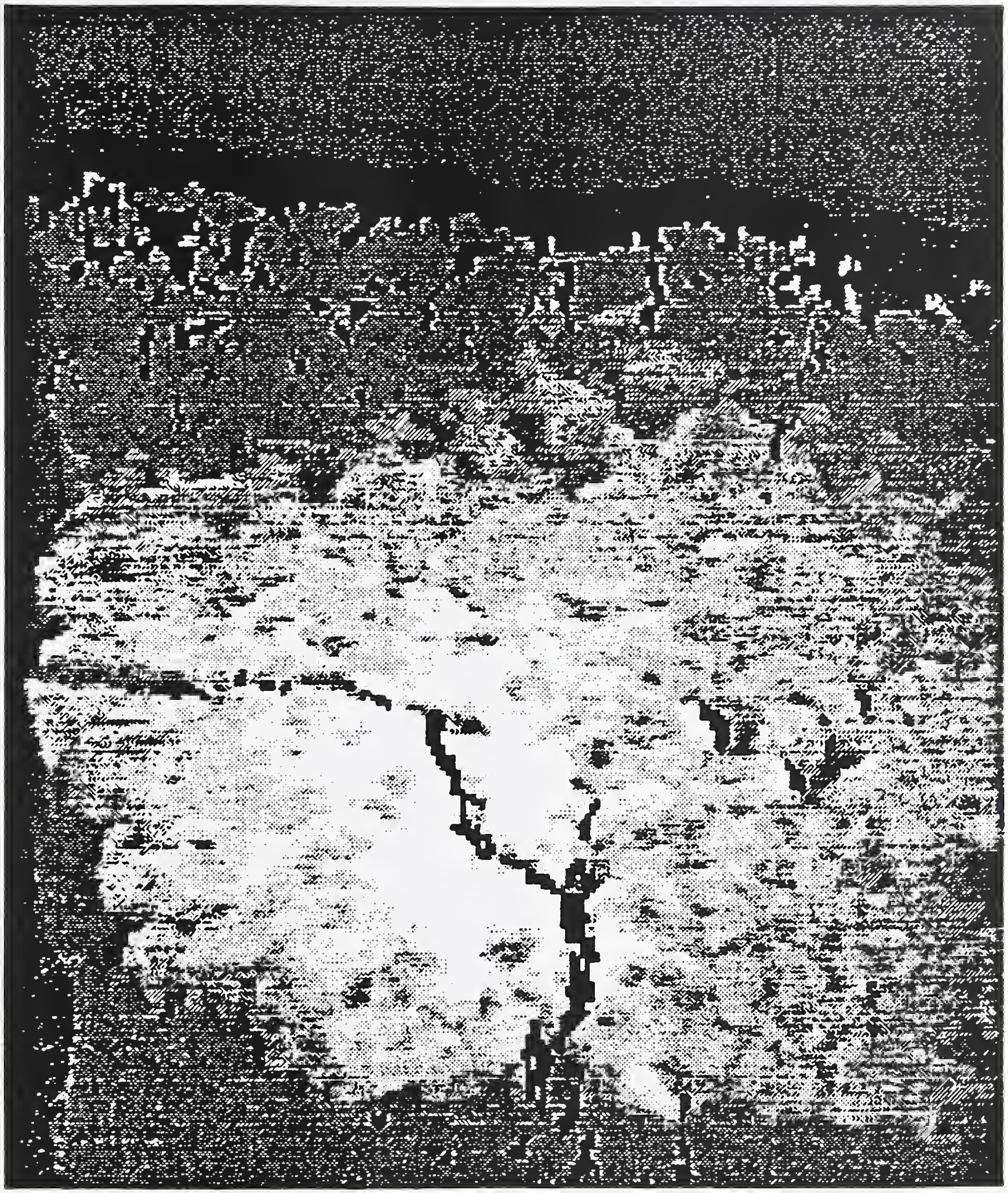


Figure 6

Z as intensity

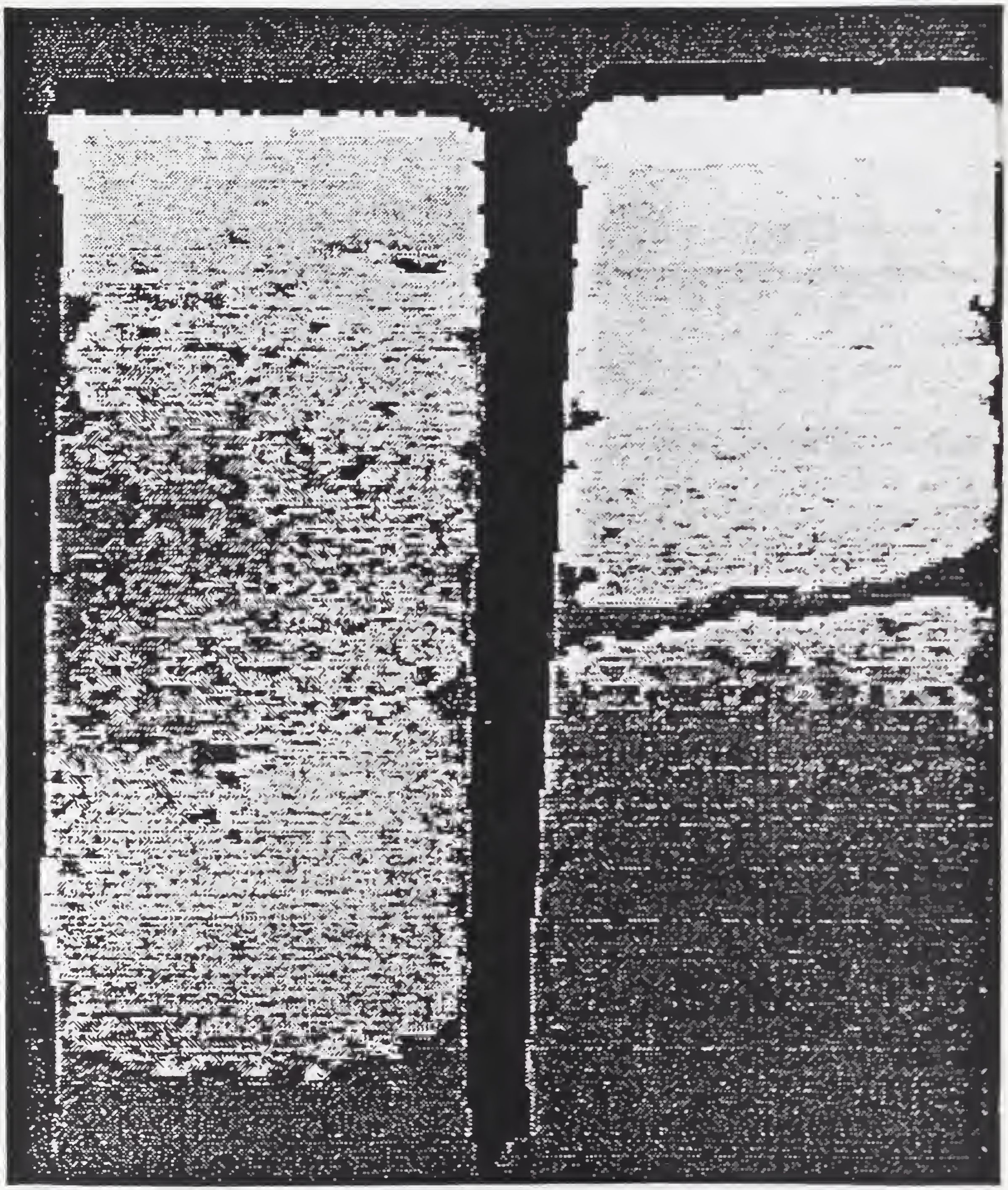


Figure 7

rolling_ball(Z)

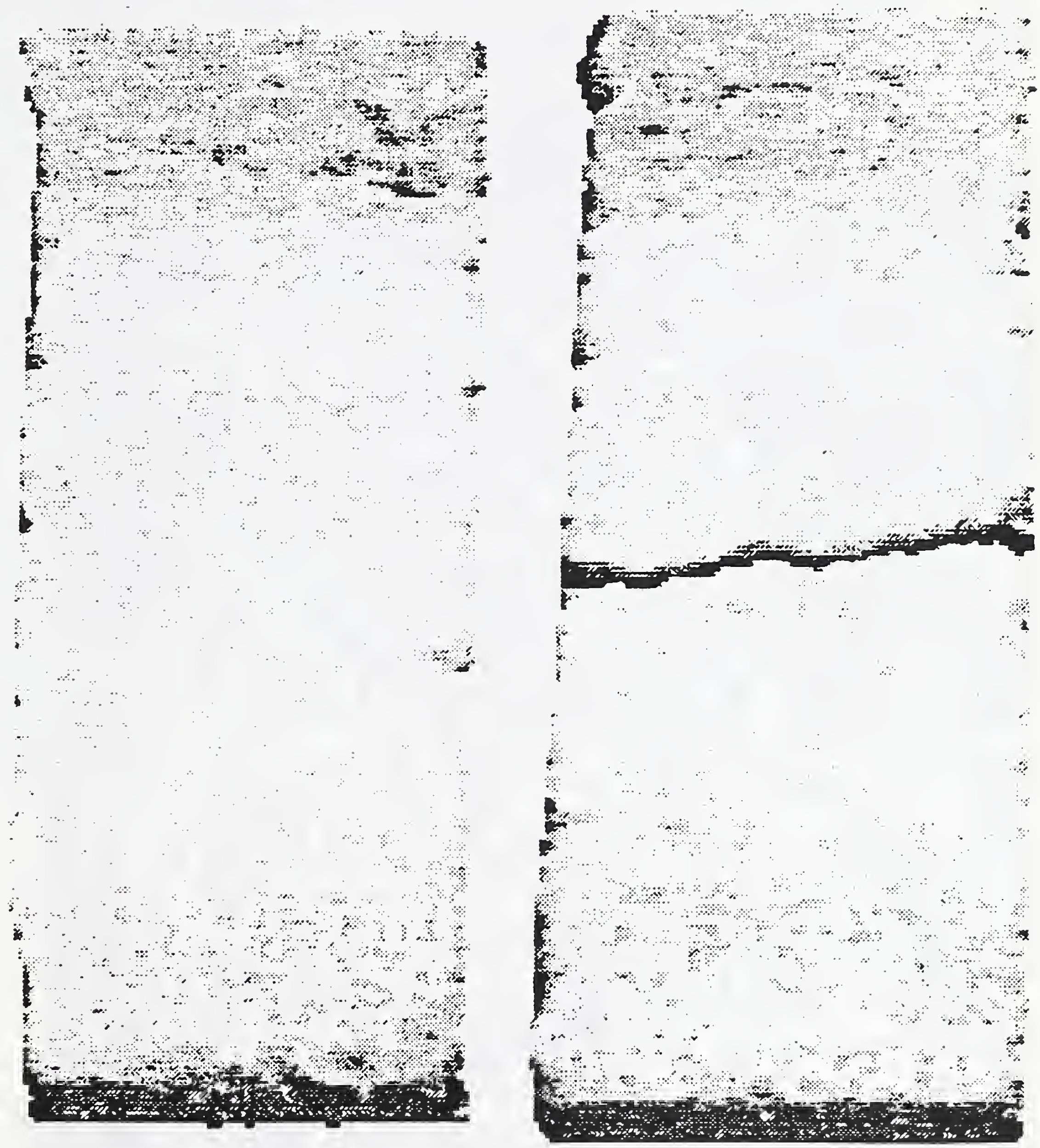


Figure 8

Photometric Data Gathering

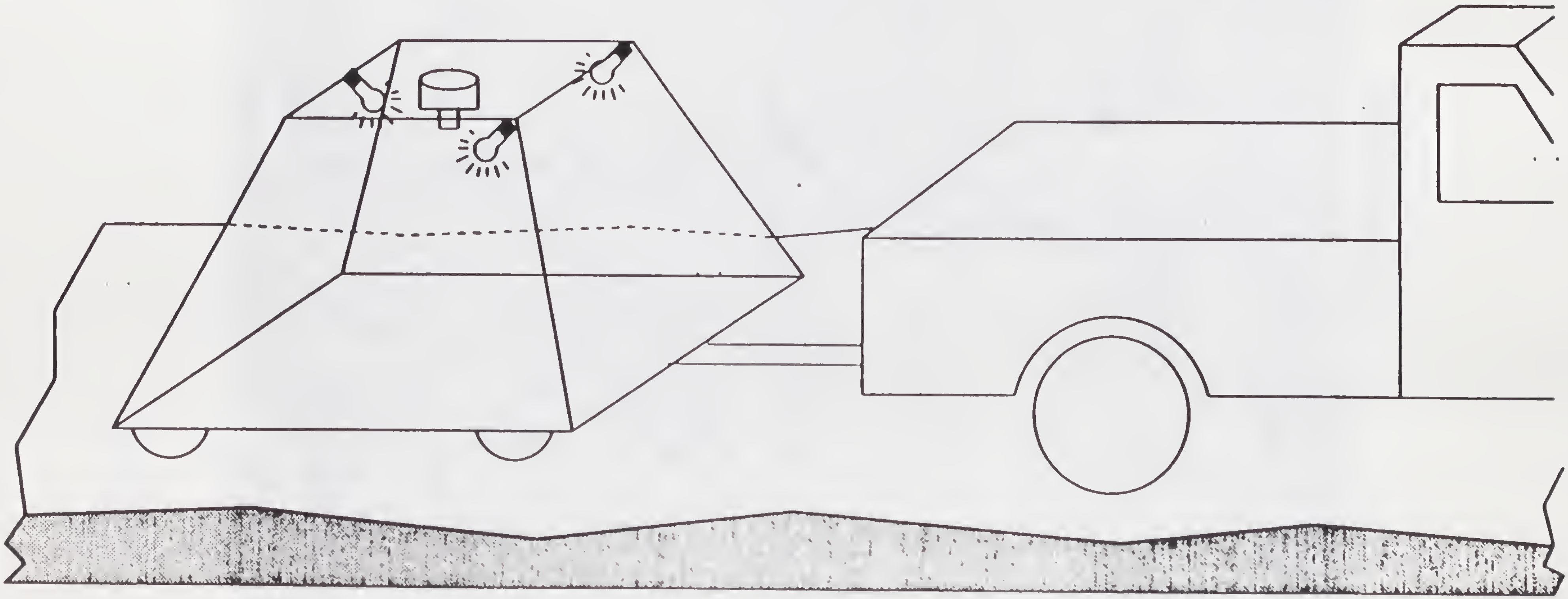


Figure 9

Robot Vision Lab, Purdue University

Intensity image

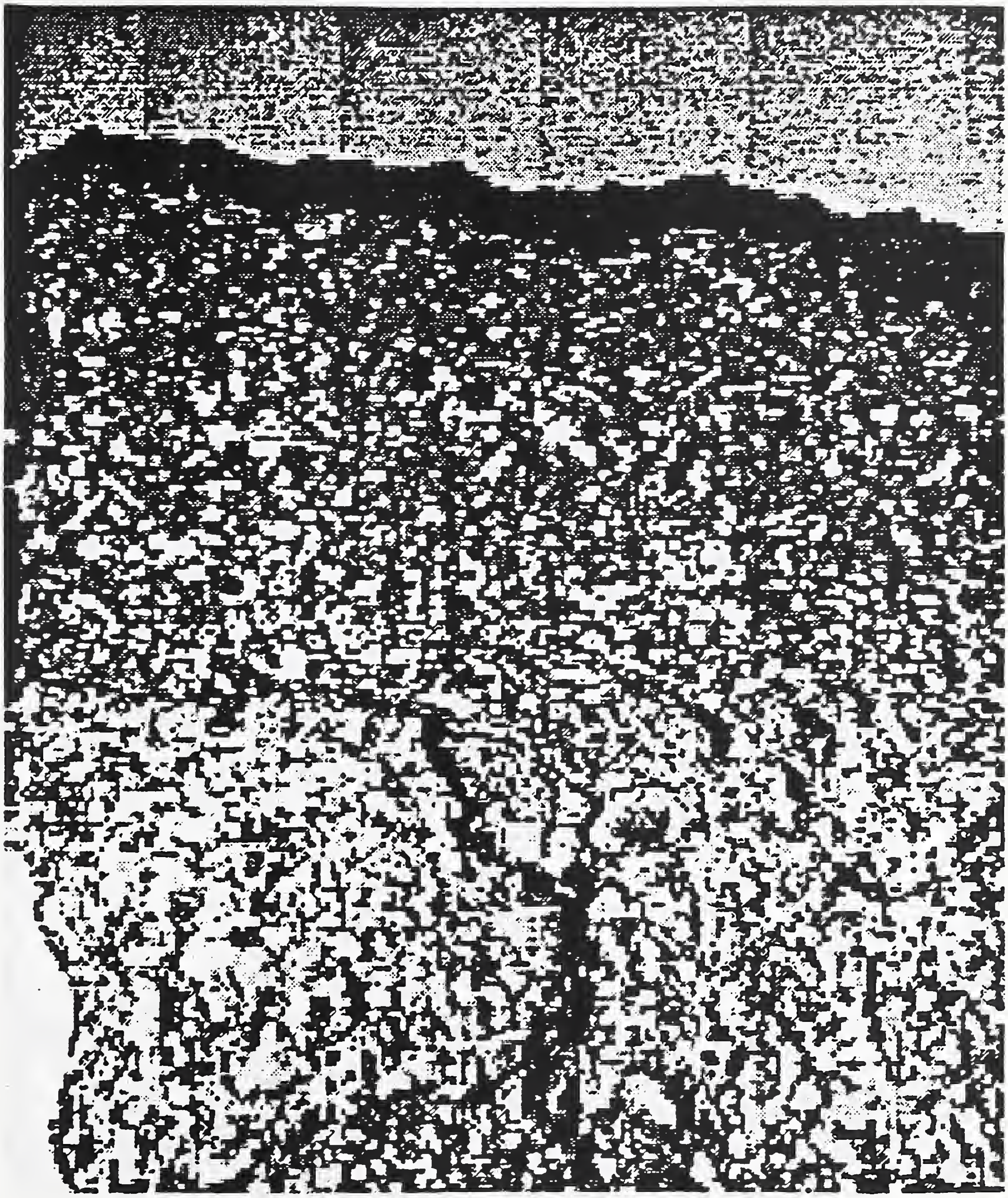


Figure 10

Intensity Image

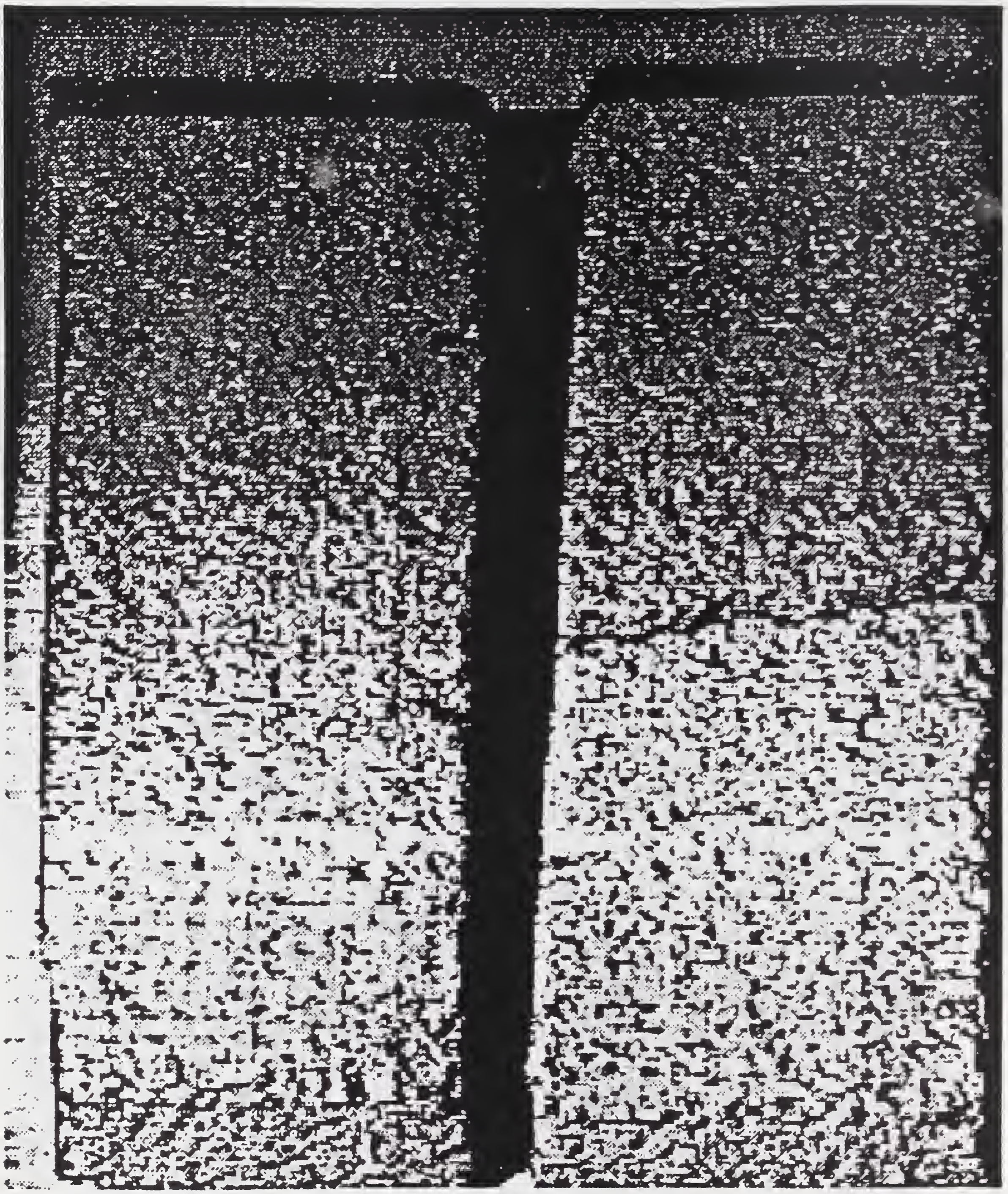


Figure 11

rolling_ball(intensity)

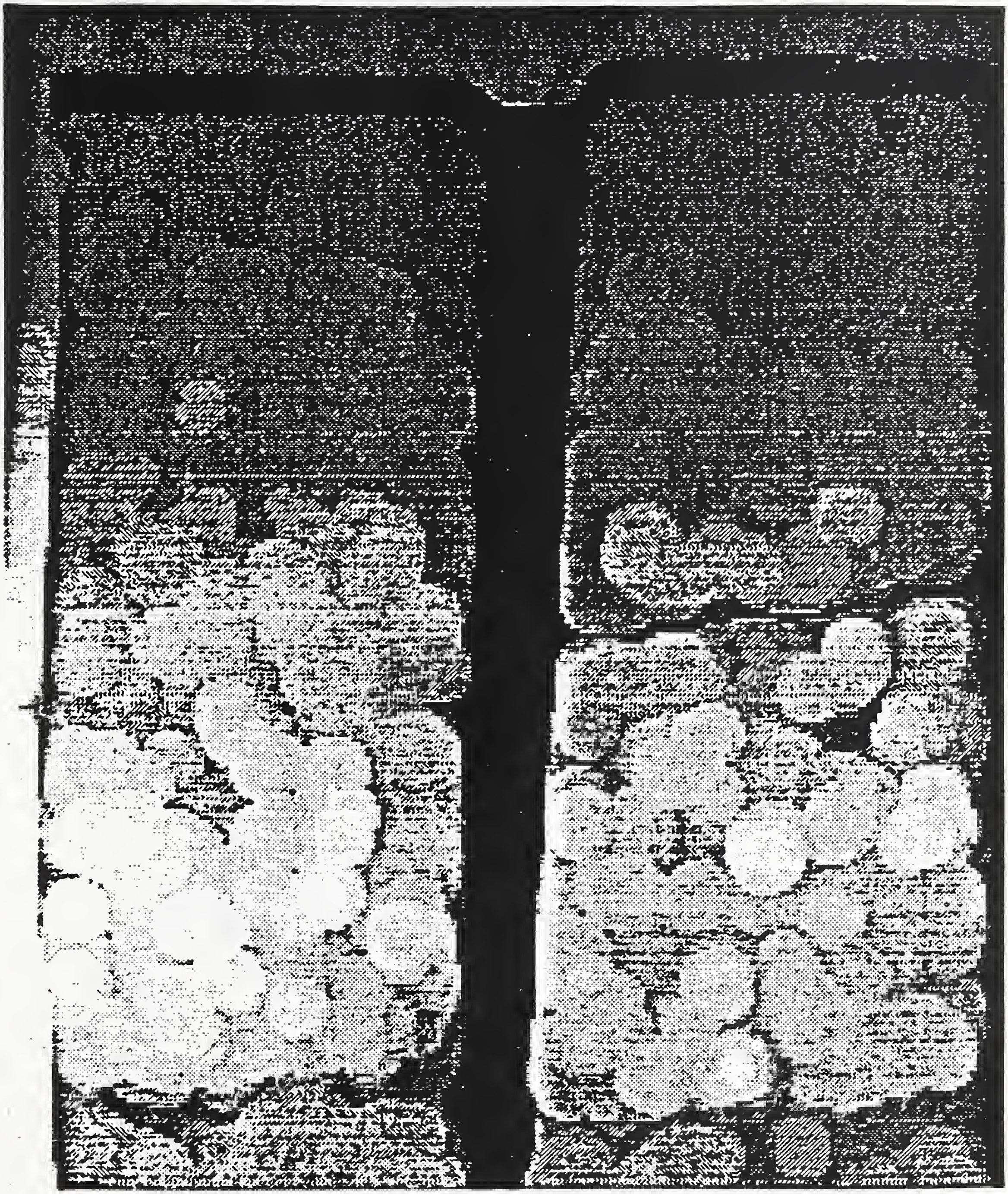


Figure 12

Purdue Robot Vision Lab's Neuro-Morph Architecture For Surface Inspection at Multiple Levels of Resolution

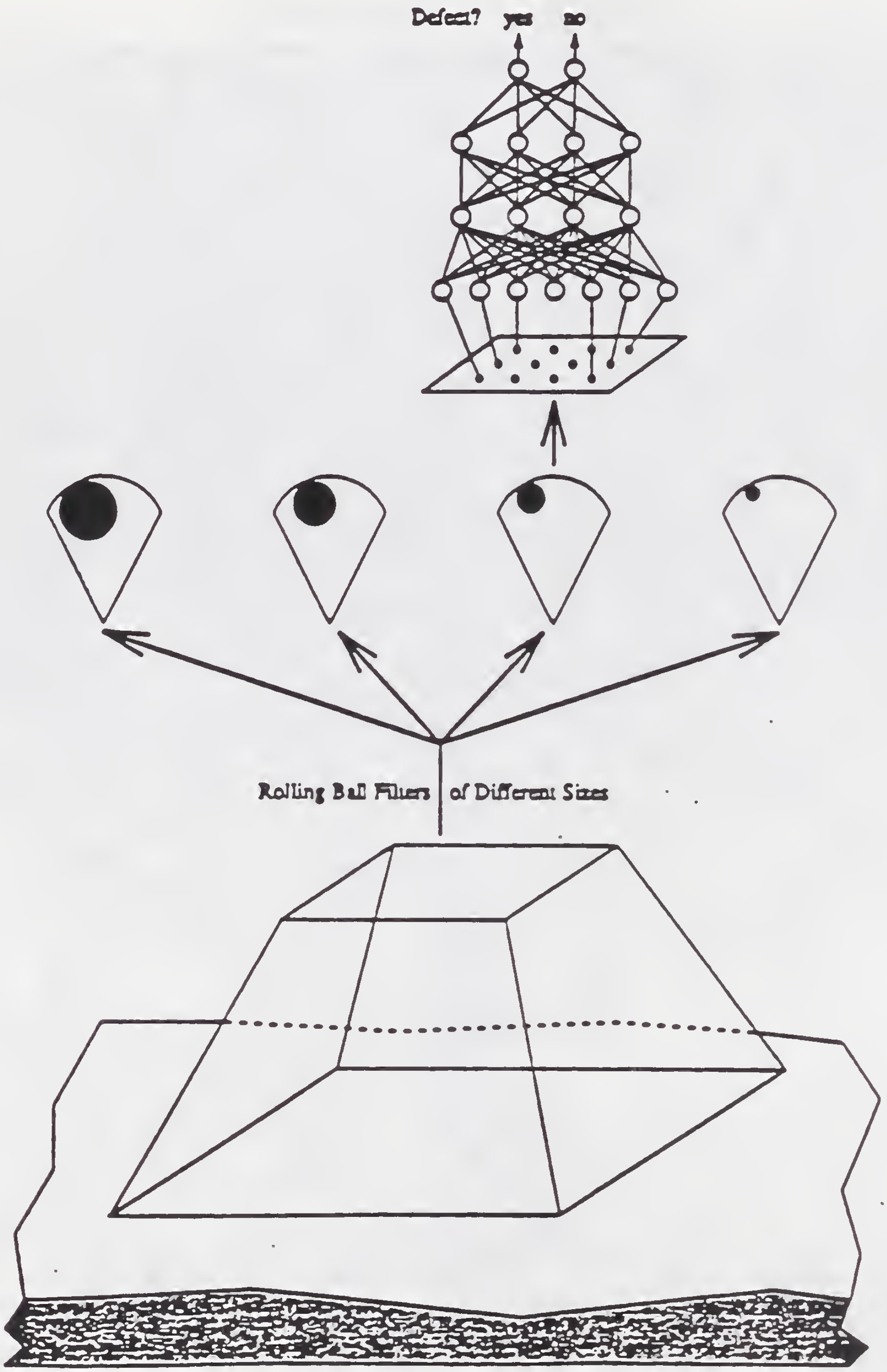


Figure 13

Use of Mathematical Morphology for analysis of pavement images

Presented by Michael M. Skolnick
Dept. of Computer Science
R.P.I.
Troy, N.Y. 12180

Abstract

Image processing algorithms based on the transformations of mathematical morphology are applied to the problems of pavement inspection. Mathematical morphology holds out some promise to these problems since it was developed out of the applications of materials analysis and pavement surfaces can be considered as particle/phase structures. The task is to classify pavement images into various distress categories, with the major components of distress involving the detection of cracks and changes in surface texture. A pavement image is processed as if it consists of various kinds of particle size distributions. Such size distributions are shown to be sensitive both to cracks and to changes in the expected texture of the pavement images. The system can be configured to have sensitivity to a wide range of expected textures via the use of a normalizing function applied to the raw size distribution data. Also, due to the reduction of image data into particle size distribution data there is a significant computational advantage to this approach. Finally, the sensitivity to phenomena beyond simple crack measures distinguishes this approach from the current state of the art.

USE OF MATHEMATICAL MORPHOLOGY FOR ANALYSIS OF PAVEMENT IMAGES

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Dimitri A. Grivas[†]

Michael M. Skolnick[‡]

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Troy, NY 12180

PROBLEM DESCRIPTION

Examine the use of mathematical morphology in automating pavement condition assessment and evaluation

- Analysis of pavement surface images obtained by a photographic or video camera
- Identifying distress
- Evaluating distress type, severity and extent according to the guidelines specified in the *Distress Survey Manual.*
- Develop numeric *indices* that indicate pavement condition for subsequent use in project level analysis

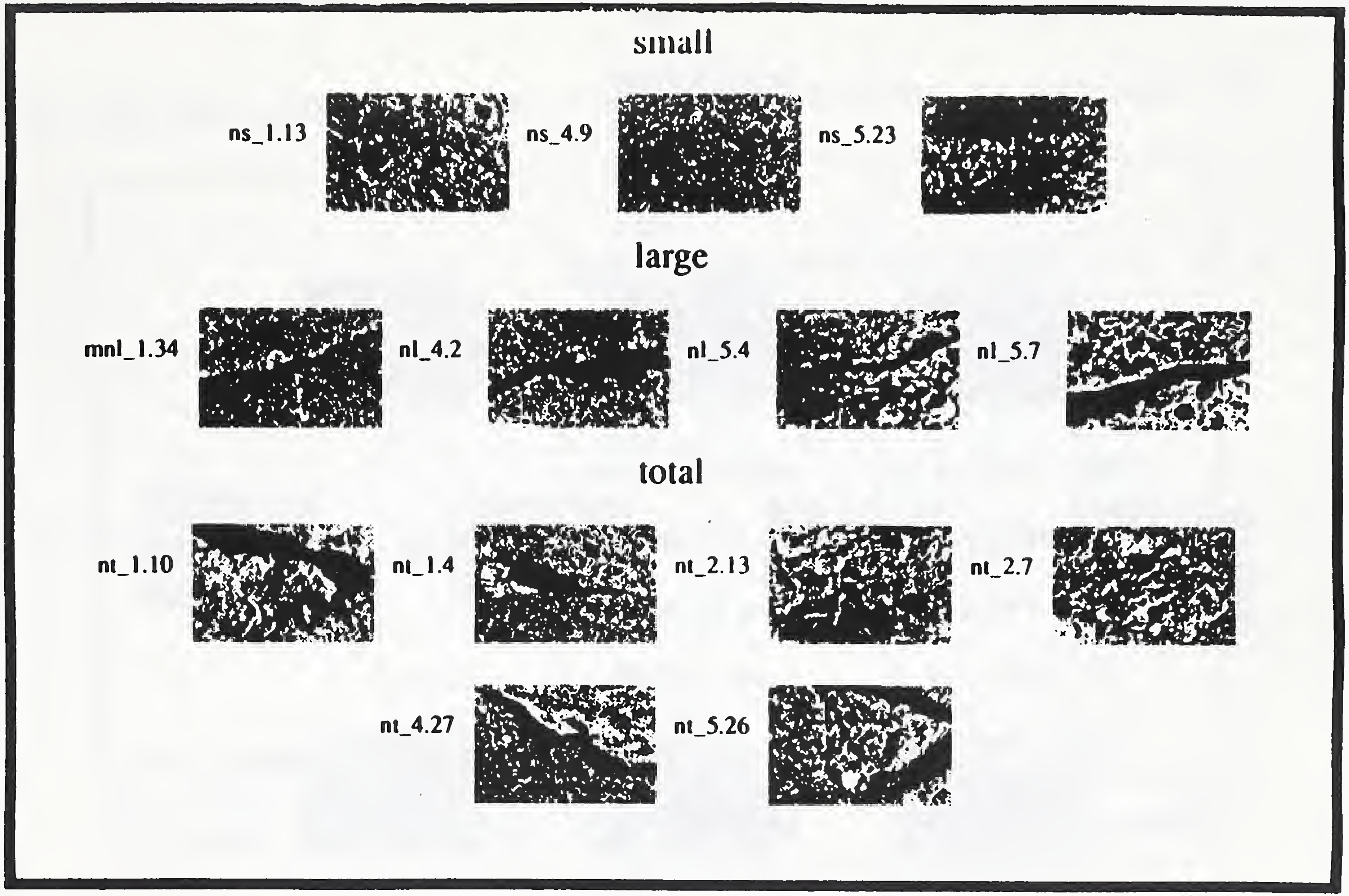


Figure 2. Pavement images belonging the class N - surface cracking of Portland cement concrete- categorized as to three levels of distress.

DISTRESS SCALE

DISTRESS TYPE	SEVERITY	DESCRIPTION	EXTENT	RATING
Slab Cracking	None	No Cracks	All Slabs	N
	Small	Tight Cracks	1 or 2 Slabs	SL
		Gen. Spall free	$\geq$ 3 Slabs	SG
(N type)	Medium	Full depth	1 or 2 Slabs	ML
		Asphalt Repairs	$\geq$ 3 Slabs	MG
	Large	Open Cracks	1 or 2 Slabs	LL
		Gen. Spall free	$\geq$ 3 Slabs	LG
	Total	Wide Spalled Cracks	1 or 2 Slabs	TL
			$\geq$ 3 Slabs	TG

The alphabet code N is used to abbreviate notation for slab cracking

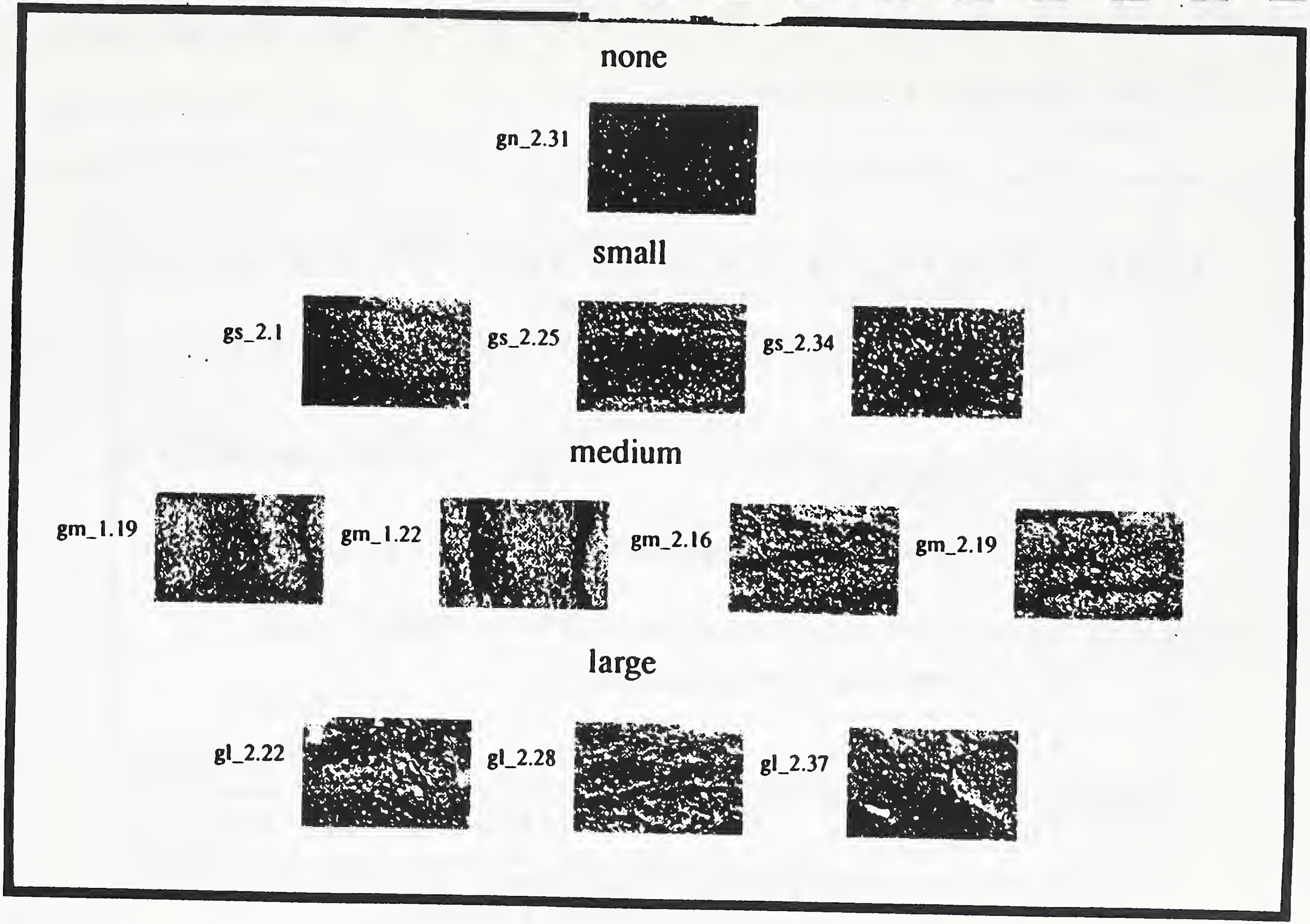


Figure 1. Pavement images belonging the class G - asphault shoulder surfaces - categorized as to four levels of distress.

DISTRESS SCALE...

DISTRESS TYPE	SEVERITY	DESCRIPTION	EXTENT	RATING
Shoulder Defects	None	No Cracks	Entire Section	N
	Small	Longitudinal Cracks or	Occasional	SL
		Transverse Cracks	Frequent	SG
(G type)	Medium	Alligator Cracks	Occasional	ML
			Frequent	MG
	Large	Material Loss or Potholes or	Occasional	LL
		Patches(all types)	Frequent	LG

The alphabet code G is used to abbreviate notation for shoulder defects

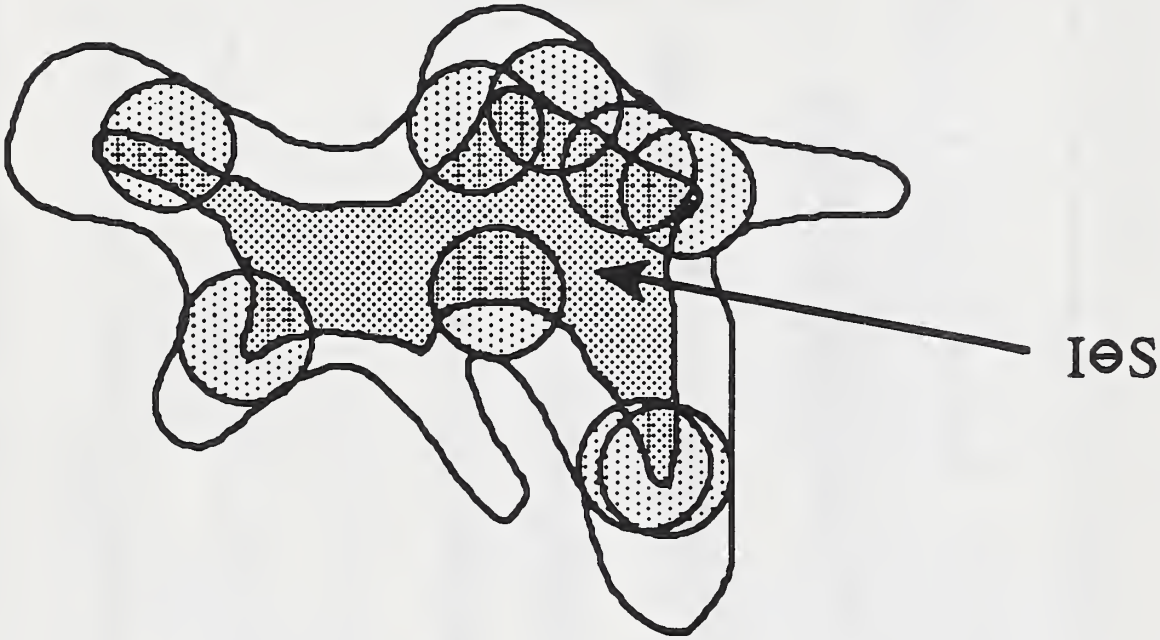
ANALYSIS OF PAVEMENT IMAGES USING MATHEMATICAL MORPHOLOGY

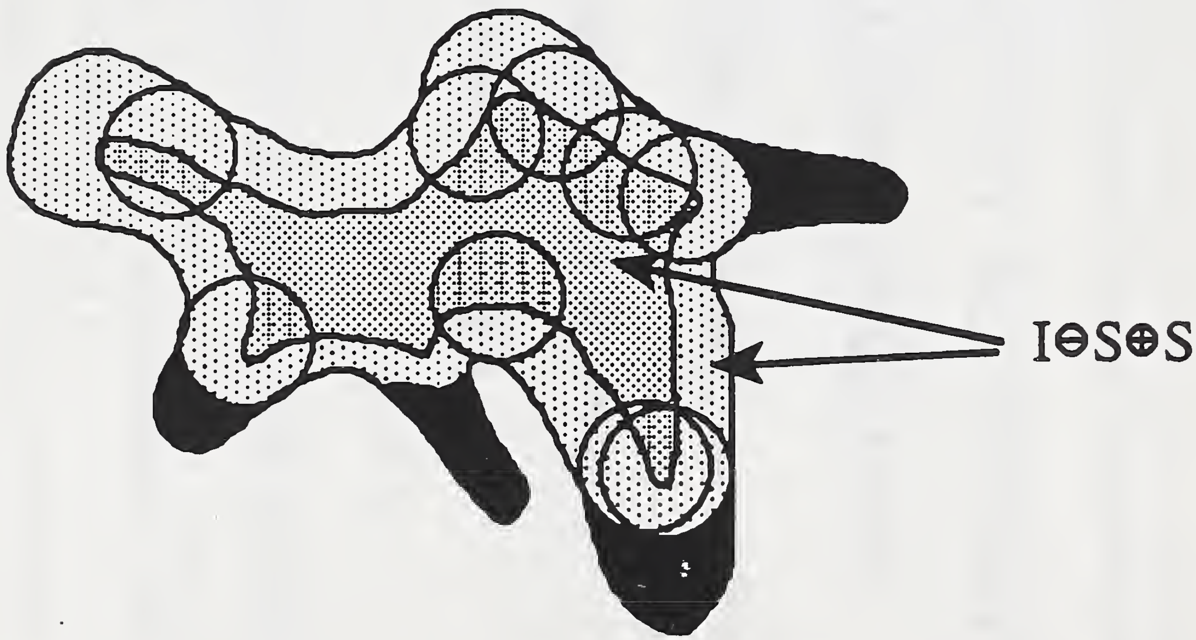
- Pavement Surface: Aggregate of particles of different sizes
  - Cracks: Linear particles of large dimensions
  - Other Defects: Particles different from the *normal* pavement texture

  Particle size distributions reveal cracks and other distresses

- Use morphological *opening distribution* for size distributions
- Normalize opening distributions to increase sensitivity to defects,

Opening: $I \circ S = I \ominus S \oplus S$





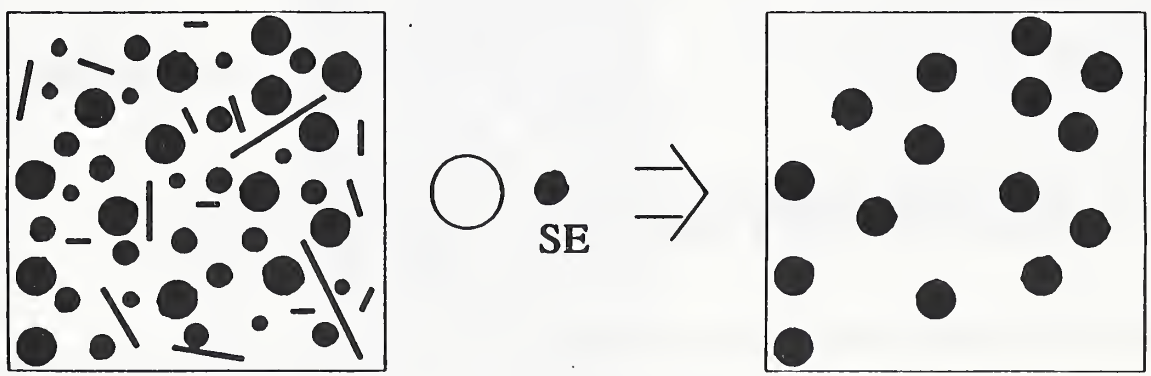
Intuitions:

"Roll" SE about interior of set to define new set

removes "peninsula" of images

MORPHOLOGICAL OPENING

- Opening by a *structuring element* removes all objects in an image inside which the structuring element cannot fit
- Removes all objects smaller than the structuring element
- Functions like a *sieve*



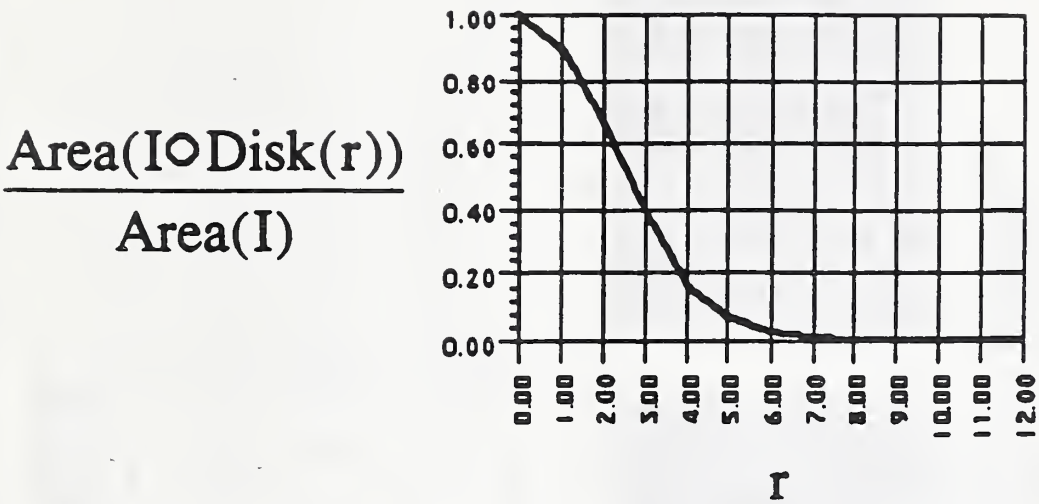
OPENING DISTRIBUTION

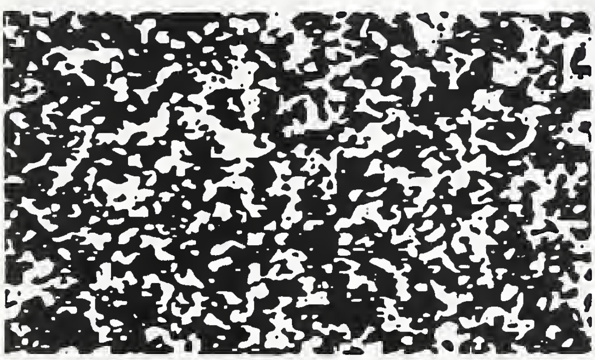
Opening distribution of an image I

- *Open* the image I with a series of structuring elements of same shape with sizes (x) increasing from '*0*' to ∞
- Plot the area of the image I after opening $(A(x))$ vs. the size of the structuring element (x)

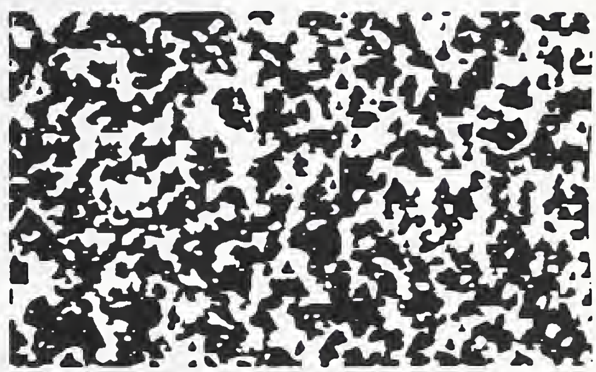
<u>Note:</u> The plot of $A(x)$ equals original area of the image when $x = 0$ and decreases to *0* when the size (x) exceeds the largest objects in the image.

opening distributions

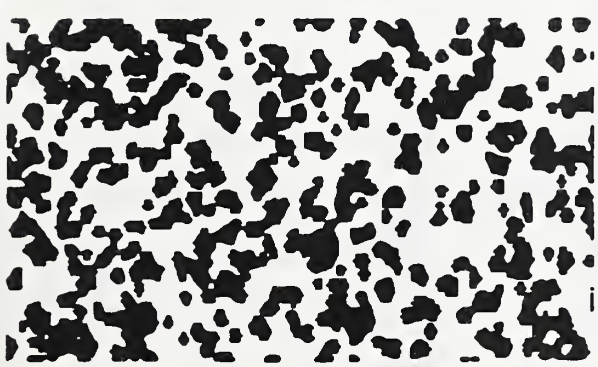




$I \circ \text{Disk}(0)$



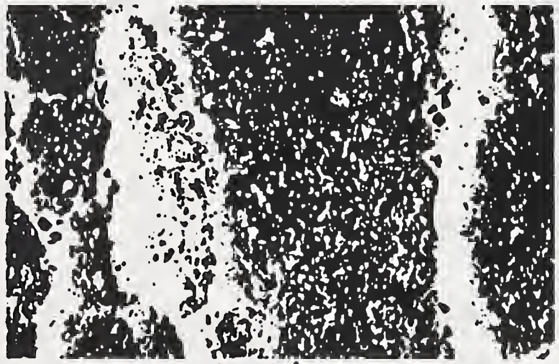
$I \circ \text{Disk}(1)$

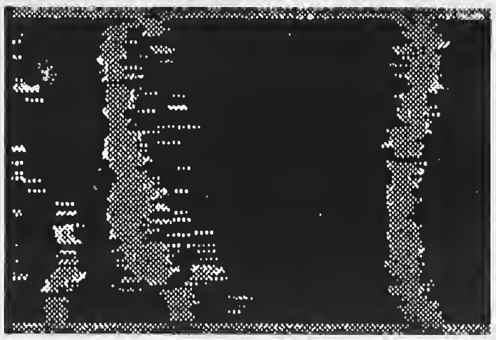


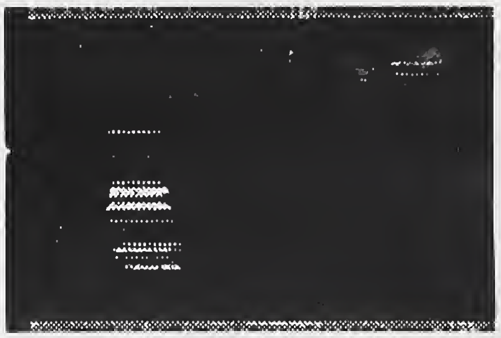
$I \circ \text{Disk}(2)$

$I \circ \text{Disk}(4)$

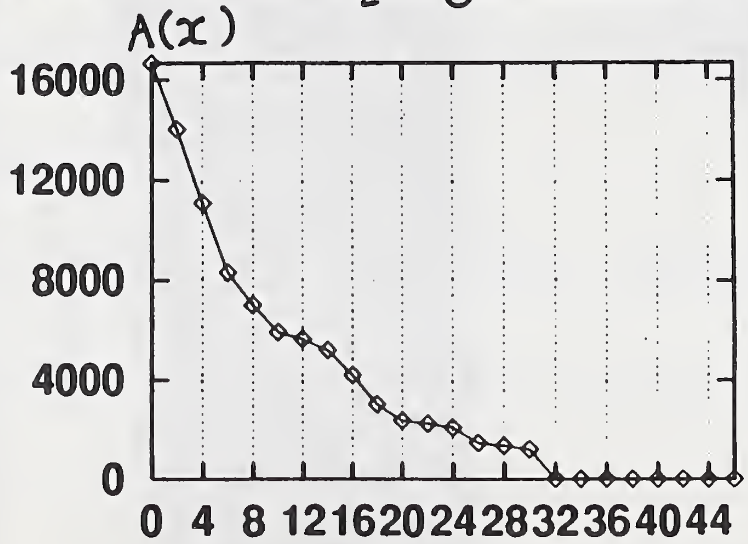
OPENING DISTRIBUTION...







SE : Horizontal Line



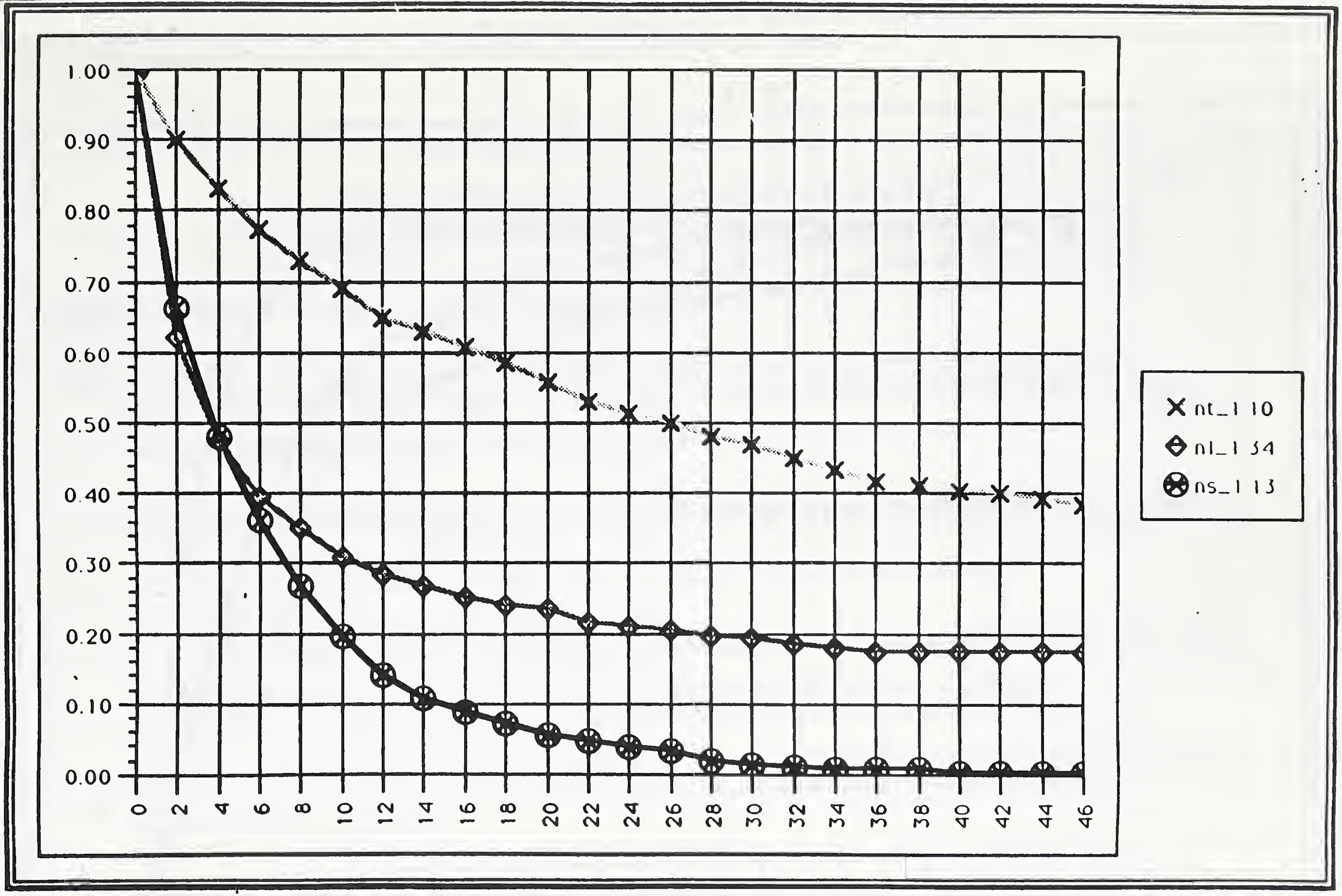


Figure 5. Opening Distributions for selection of 3 images in distress class N. The x-axis values - for all distribution graphs - are the lengths of horizontal lines used to open the three binary images. The y-axis is the percentage area remaining after each opening operation. The distress categories of the curves are displayed in grey-scales such that small (ns_1.13) distress is darkest, large (nl_1.34) distress is medium dark and total (nt_1.10) is lightest; visualize the grey-scales as representing increasing levels of pavement deterioration from darkest to lightest.

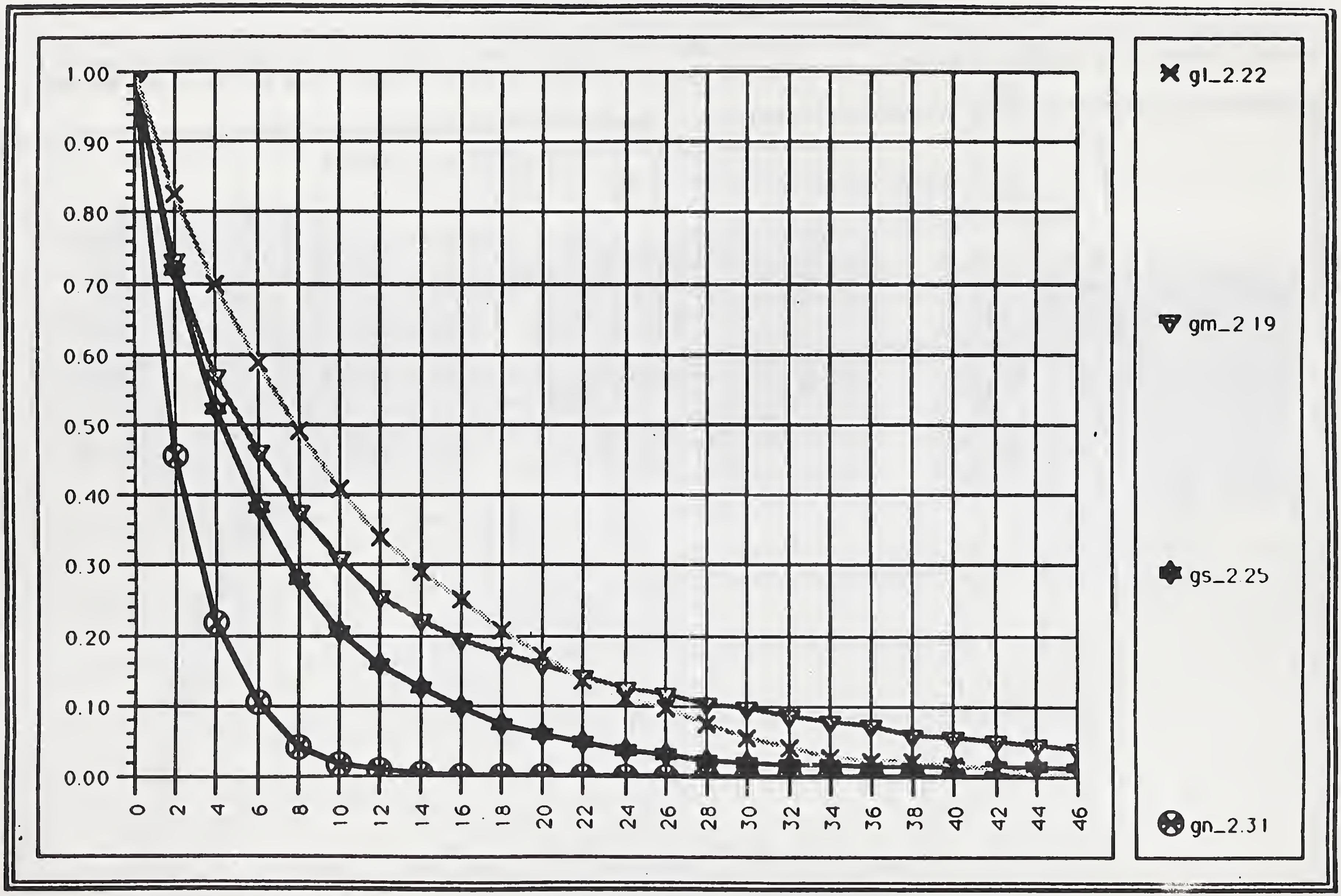


Figure 9. Four selected opening distributions from distress class G which illustrate the difficulties in using the raw opening distributions to realize the distress types. Note the crossing over of medium and large distress categories at linear structuring element size of 22.

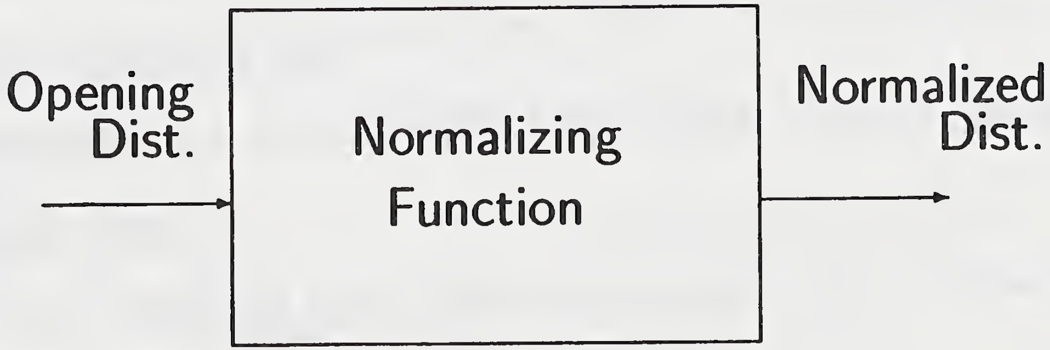
CURRENT APPROACH

Uses a-priori morphological models

- Models are developed for *ideal* or non-defective textures based on size distributions
- Size distributions are computed for a given texture using opening and closing distributions
- Deviations in the extracted distributions from the *ideal* distributions predicted by the model are identified as defects
- The magnitude of the deviations provides information on the severity of the defects
- Rough indication of the location of defects (as well as texture inhomogeneities) is obtained from *centroid movements*

NORMALIZATION SCHEME

- Normalizing Function: incorporates a-priori knowledge into Opening Dist.



- Normalized Dist. is more sensitive to any departures from the *normal* texture described by the a-priori knowledge

MORPHOLOGICAL MODELING...

- The **Gaussian Number of Particles (GNOP)** model:
  - The number of particles exhibit a gaussian distribution with a mean scale T with μ_T particles at scale T i.e.

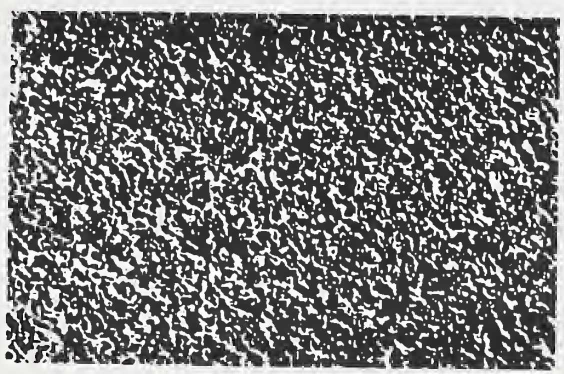
$$N_t = \mu_T \cdot e^{-\frac{(t-T)^2}{2\sigma^2}}$$

where N_t is the number of particles at scale t

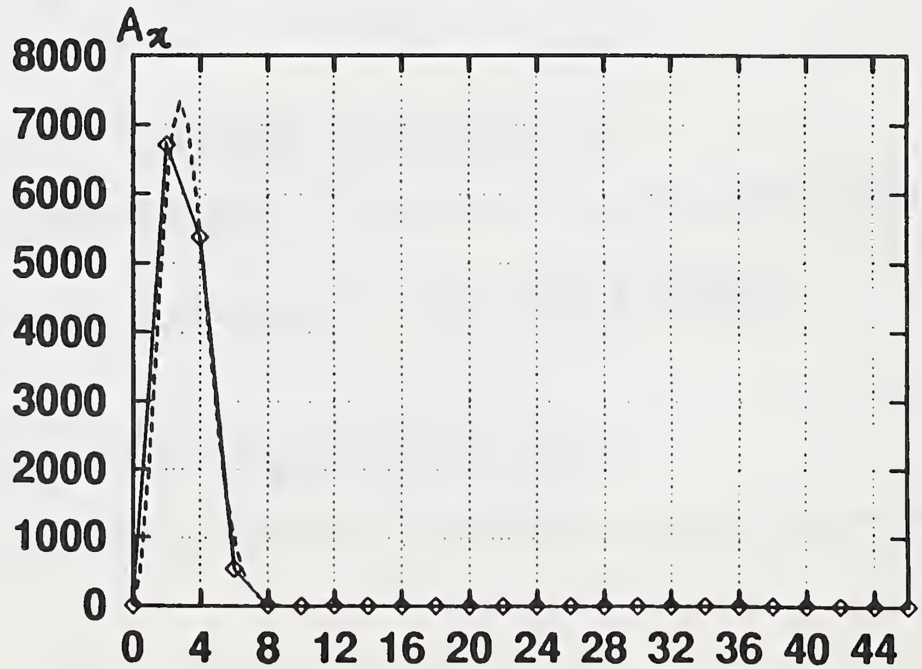
SIZE DISTRIBUTION OF A PAVEMENT IMAGE WITH NO DISTRESS

Image: *gn_2.31*

Size distribution: Plot of $A_x = A(x) - A(x-1)$ vs. x



gn_2.31

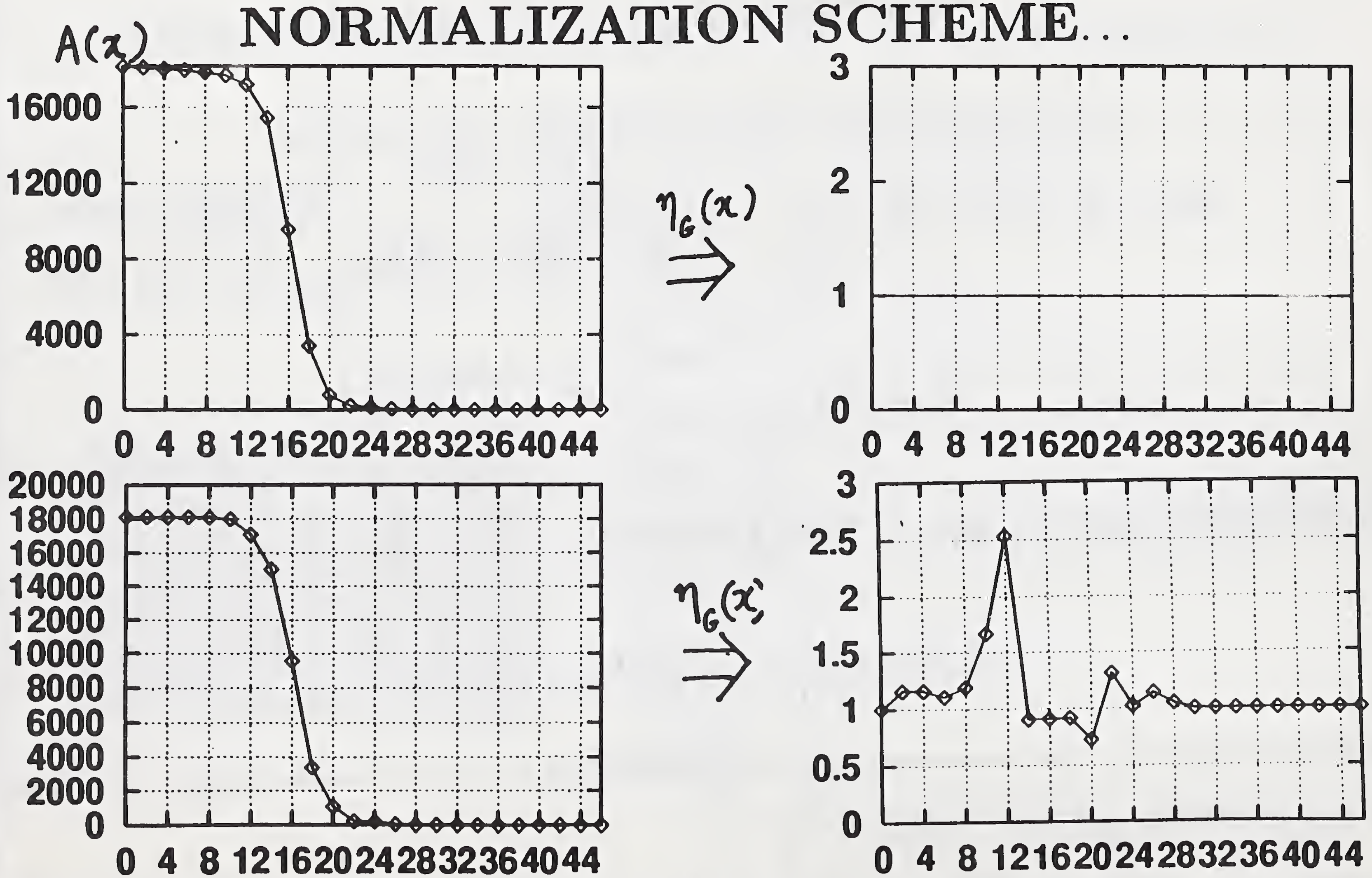


GAUSSIAN MODEL

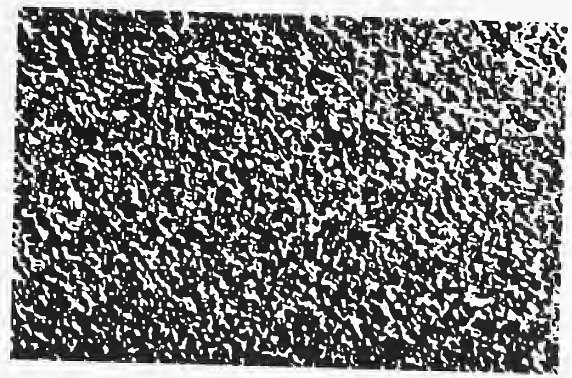
Gauss Normalizing Function (Opening Dist.) $\Rightarrow$ Normalized Dist.($\eta_G(x)$)

$$\eta_G(x) = \begin{cases} \dfrac{A(0)}{\sqrt{2\pi}\sigma\mu_T \cdot T}, & \text{if } x = 0 \\[2ex] \dfrac{A(x) - A(x-1)}{\mu_T x e^{-\frac{(x-T)^2}{2\sigma^2}}}, & T - 3\sigma \leq x \leq T + 3\sigma \\[2ex] \dfrac{A(x) - A(x-1)}{x} + 1, & \text{otherwise} \end{cases}$$

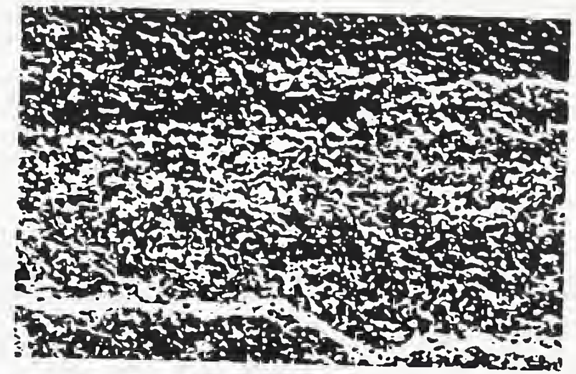
NORMALIZATION SCHEME...



TEST IMAGES FROM 'G' CATEGORY

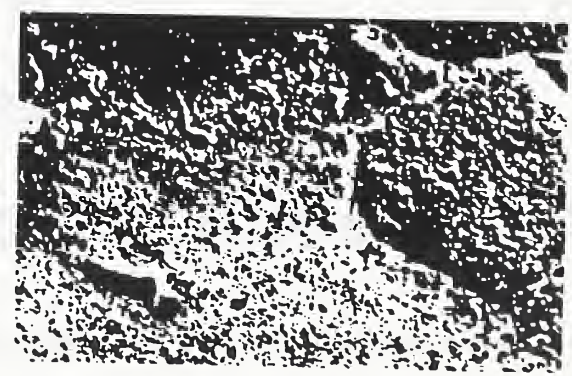


gn_2. 31



gs_2.25

gm_1.22

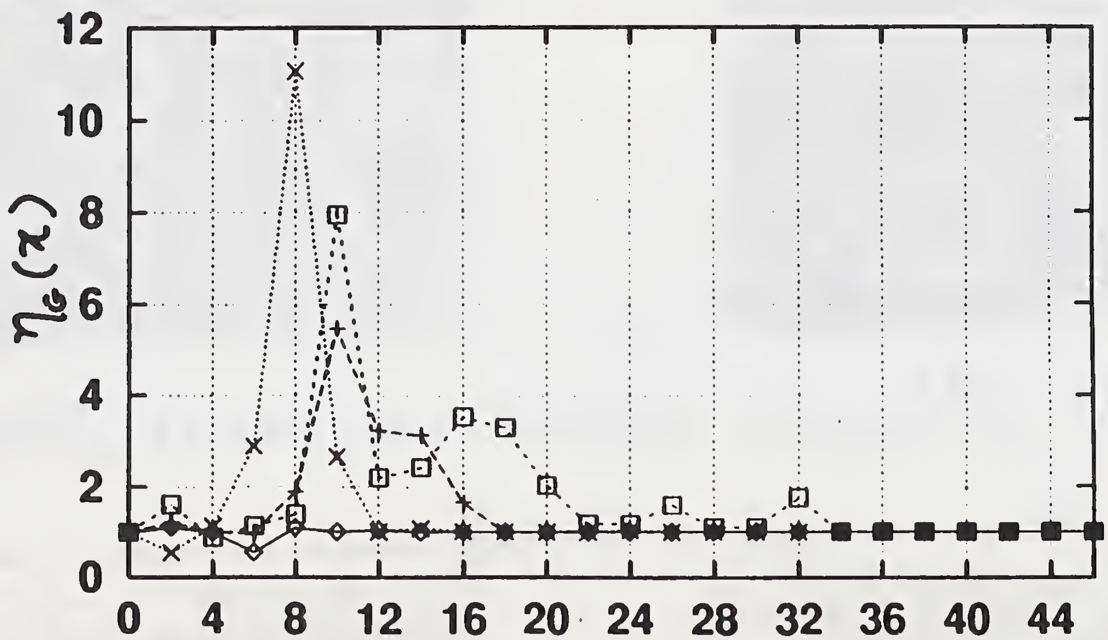


gl_2.37

NORMALIZED DISTRIBUTIONS OF TEST IMAGES

Images: $gn\_2.31$ (◇), $gs\_2.25$ (+), $gm\_1.22$ (□) and $gl\_2.37$ (×)

Gaussian Parameters: $T = 1.0$, $\sigma = 2.0$, $\mu_T = 12500$



MOTIVATION

- Applications of Pavement Distress Evaluation
  - Characterization of different textures and their relation to pavement condition
  - Characterization of inhomogeneities in texture and their relation to different types of pavement distress
  - Efficient implementation of algorithms for distress surveys

CONCLUSIONS

- The current approach provides overall severity measures and discriminates between different types of distresses
- Particle Distributions provide information about pavement distresses
  - Reveal cracking and other types of distress
  - Provides a single technique to analyze different types of distresses unlike many existing algorithms; results in significant computational savings

FUTURE WORK

- Test the algorithm on more images from different pavement types, with different types of distresses
- Discriminate between different types of cracking – longitudinal, transverse, alligator etc.
- Analyze distresses other than cracking to discriminate between pitting, spalling, milling etc.
- Derive numeric *indices* that estimate the condition of the pavement, and subsequently provide useful information for project level analysis

A Neural Network-Based Methodology for Automated Detection and Classification of Highway Pavement Surface Cracking

Mohamed Kaseko and Stephen Ritchie
Institute of Transportation Studies
University of California
Irvine, CA 92717

One of the most important elements of an effective pavement management system is the collection and interpretation of pavement surface distress data. Current procedures for carrying out this process typically involve on-site visual inspection and condition evaluation by field personnel. This method is a subjective, slow process that is also labor-intensive, tedious and often dangerous.

Recent developments in automation of this process have principally been based on the application of machine vision and conventional image processing techniques. Although these developments have considerably advanced the state-of-the-art of automated pavement distress evaluation, their performance has been limited by the inherent shortcomings of conventional image processing techniques applied to pavement images.

The objective of this research was therefore to develop and demonstrate the feasibility of an alternative methodology that is based on integration of conventional image processing techniques and artificial neural network (ANN) models. The research focused on application of ANN models as pattern classifiers for image interpretation and classification, resulting in the development of approaches for automatic thresholding of the images, and for detection and classification of surface cracking in each image, using a multi-layer feed-forward (MLF) neural network model. About 250 of the asphalt concrete pavement images acquired by the firm PASCO USA INC. for the US Strategic Highway Research Program (SHRP) were used in this research.

The results obtained have shown that MLF was able to detect and correctly classify about 98% of the images with transverse and longitudinal cracking, and 86% of those with alligator and block cracking. A method for computation of severity and extent measures was also developed. These results have clearly demonstrated the potential for application of the neural network-based approach in detection and classification of pavement surface cracking.

This research was part of an effort aimed at developing an AI-based system that would automate much of the pavement data acquisition, interpretation, and evaluation process, and capture the experience and judgment of expert pavement engineers in performing condition assessments and identification of appropriate maintenance and rehabilitation strategies. One of the basic elements of the system already exists in prototype form. It is a microcomputer-based knowledge-based expert system known as Pavement Rehabilitation Analysis and Design Mentor (PARADIGM), which takes as input pavement distress and other data and performs condition assessment and recommends repair, maintenance and rehabilitation strategies.

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DIMENSIONAL MEASUREMENT THROUGHOUT LIFECYCLE OF PAVEMENT STRUCTURES

PSI is developing scanning laser based pavement measurement systems.
This presentation explains the basis for these new products.

REQUIREMENTS, CURRENT PRACTICE

AND THE POTENTIAL OF LASER MEASUREMENT TECHNOLOGY

William J. Herr, President of PHOENIX SCIENTIFIC INC.
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PAVEMENT STRUCTURES LIFE CYCLE STAGES

The next 5 viewgraphs outline the status of dimensional measurement in each of these pavement life cycle stages as background for evaluation of the potential of applying laser scanning technology.

- Site and Route Survey
- Site and Route Preparation
- Construction and Commissioning
- Maintenance and Refurbishment
- Resurfacing and Replacement

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SITE AND ROUTE SURVEY

- REQUIREMENTS
  - Minimize Cost: cut and fill operations
  - Optimize Drive Path Quality: grade and curvature
- CURRENT PRACTICE
  - Traditional Survey Techniques
  - Aerial: gross routing decisions: topographic efforts limited and costly
- MODERNIZATION STATUS
  - Available: Geometric Design Computing Technology
  - Needed: Topography Sensing and Interface to S/W

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SITE AND ROUTE PREPARATION

- REQUIREMENTS
  - Excavation
  - Fill
  - Leveling/Smoothing
  - Compaction
- CURRENT PRACTICE
  - Traditional Surveying
  - Laser Grader Control
  - Roller vibrational sensing for compaction
- MODERNIZATION STATUS
  - Ongoing: Real-time on-line assessment using laser grade control
  - Needed: Topography Sensing and Interface to S/W

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CONSTRUCTION AND COMMISSIONING

- REQUIREMENTS
  - Sublayers and Asphalt Compaction
  - Material Deposition Paving Machines
- CURRENT PRACTICE
  - Contracts performed on basis of material volume specified
  - Automatic screed control for grade and crossfall using guide wires or laser plane sensing
  - Profilograph 24 Hrs after deposition
- MODERNIZATION STATUS
  - Automatic screed control for grade and crossfall using laser plane sensing

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MAINTENANCE AND REFURBISHMENT

- REQUIREMENTS
  - ISTEA Pavement Management
    - Rutting, Roughness, Distress, Bearing Capacity
- CURRENT PRACTICE
  - Rutting: 3 sensors, 1 reference & 1 per wheel path
  - Roughness: Ride Meter
  - Distress: Visual surveys and Continuous photo
  - Deflection: Falling Weight Deflectometer
- MODERNIZATION STATUS
  - Rutting: more single point sensors
  - Roughness: Inertial profilometer
  - Distress: Video collection with machine assisted post processing
    Structured light with laser line illumination
  - Deflection: None

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RESURFACING AND REPLACEMENT

- REQUIREMENTS
  - Threshold for selection
    - Integrated PM data critical
  - Data for design of action plan
- CURRENT PRACTICE
  - Budget driven prioritizing and planning
- MODERNIZATION STATUS
  - Design for planned service
  - Geometric design for optimization
    - Minimize grinding and new material

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RANGE MEASUREMENT TECHNOLOGY

This is an overview of the sensing technology that can be applied to dimensional characterization of pavements.

- CONTACT
  - Limited to static applications
- NON-CONTACT
  - ACOUSTIC
    - Dominant in robot obstacle detection
    - Low resolution due to acoustic wavelength
  - RADAR
    - Dominant in military applications
    - Moderate resolution at high cost of receiver array
    - Issues: Target impedance and EMI safety
  - OPTICAL
    - Dominant in machine vision
    - High resolution and bandwidth
    - System optimization required

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OPTICAL RANGING TECHNIQUES

- TIME OF FLIGHT
  - Data rate limited by laser pulse rate
  - Leading edge detection requires large bandwidth (1/2t)
- TRIANGULATION
  - Point Sensor
  - Dominant in highway applications
- MACHINE VISION
  - Structured Light and Stereography
- INTERFEROMETRY
  - Limited to surface with variations << λ of laser light
- AM PHASE & FM COHERENT DETECTION
  - No focus required
  - Tolerant of wide range of ambient lighting and reflectivity

This is an overview of the optical sensing technology that can be applied to dimensional characterization of pavements.

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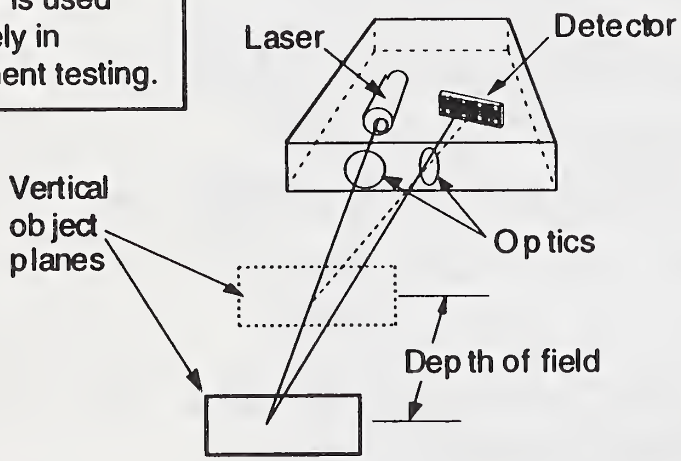
TRIANGULATION/MACHINE VISION

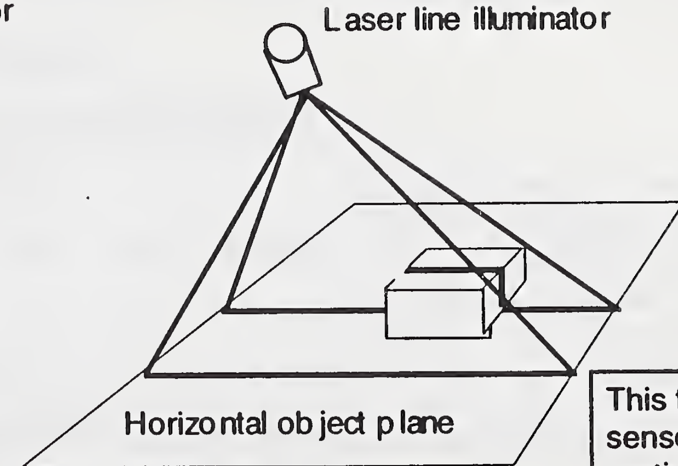
POINT SENSOR

This type of sensor is used routinely in pavement testing.



- Non-scanning
- Limited range (Range vs Resolution Trade-off)
- Resolution limited by pixels in detector

STRUCTURED LIGHT



This type of sensor is used routinely in machine vision and is becoming more common with advances in computer based CCD cameras.

- Requires imaging with focus control
- Computational intensive
- Resolution limited by pixels in detector

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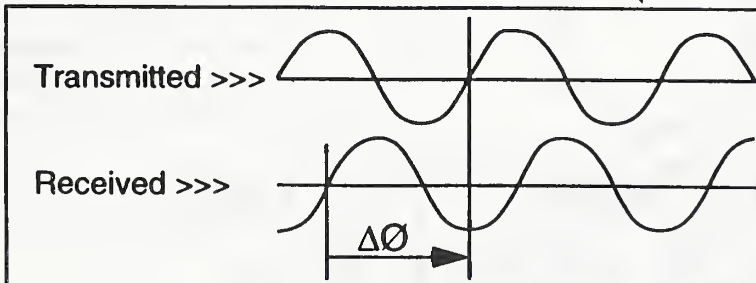
AM MODULATION PHASE MEASUREMENT

- LASER OUTPUT AMPLITUDE MODULATED
  - Single stable frequency (f_m)
- RANGE AMBIGUITY INTERVAL
  - $R_{AINT} = c/(2f_m) = \lambda_m/2$
- RANGE PROPORTIONAL TO PHASE SHIFT
  - $R = R_{AINT} \cdot \Delta\varnothing / 360°$

f_m (MHz)	λ_m (Feet)	R_{AINT} (Feet)
1	984.3	492.1
10	98.4	49.2
20	49.2	24.6
50	19.7	9.8
100	9.8	4.9
120	8.2	4.1
150	6.6	3.3

This principal is used routinely in electronic distance measurement for surveying.



$\Delta\varnothing = 270° = \frac{3}{2}\pi$ Radians

$R = \frac{270°}{360°} R_{AINT} = 0.75\ R_{AINT}$

- PATENT APPLIED FOR -

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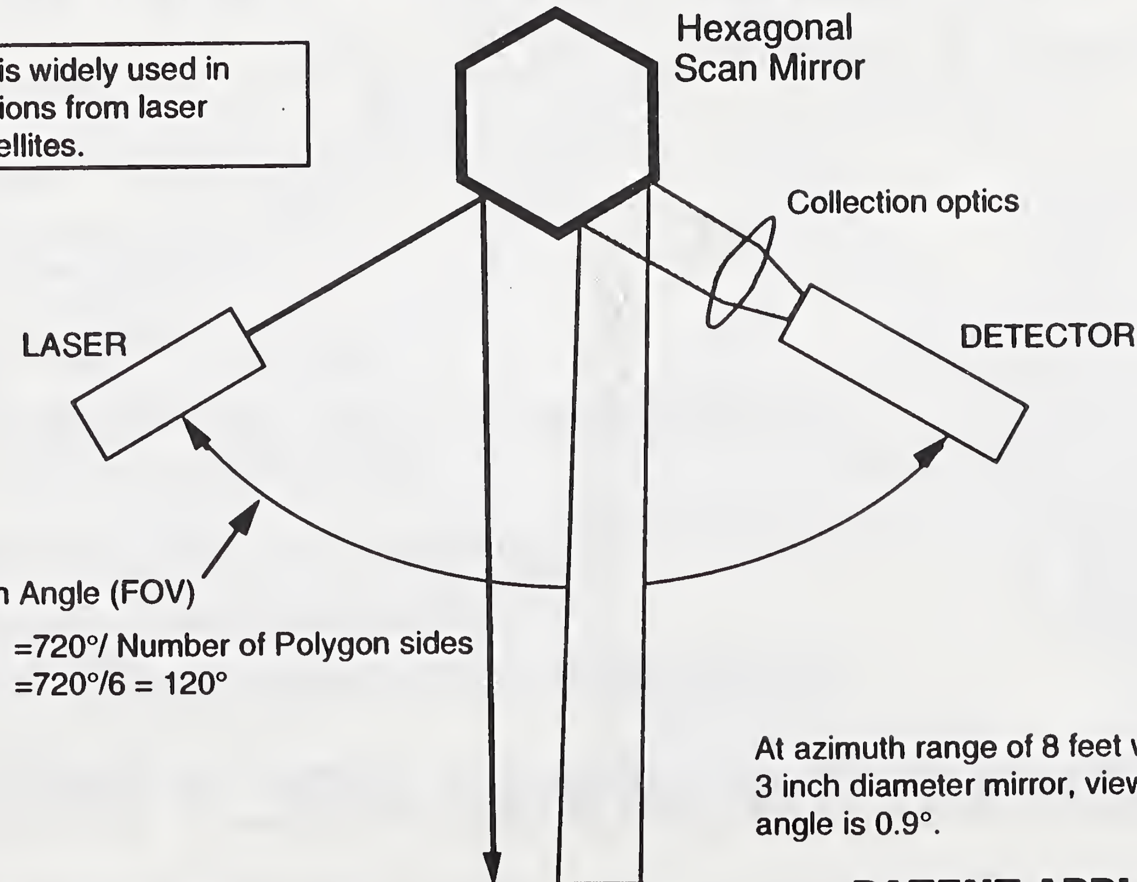
POLYGON SCANNING OPTICAL ARCHITECTURE

This principal is widely used in many applications from laser printers to satellites.



Maximum Scan Angle (FOV)

=720°/ Number of Polygon sides
=720°/6 = 120°

At azimuth range of 8 feet with 3 inch diameter mirror, viewing angle is 0.9°.

- PATENT APPLIED FOR -

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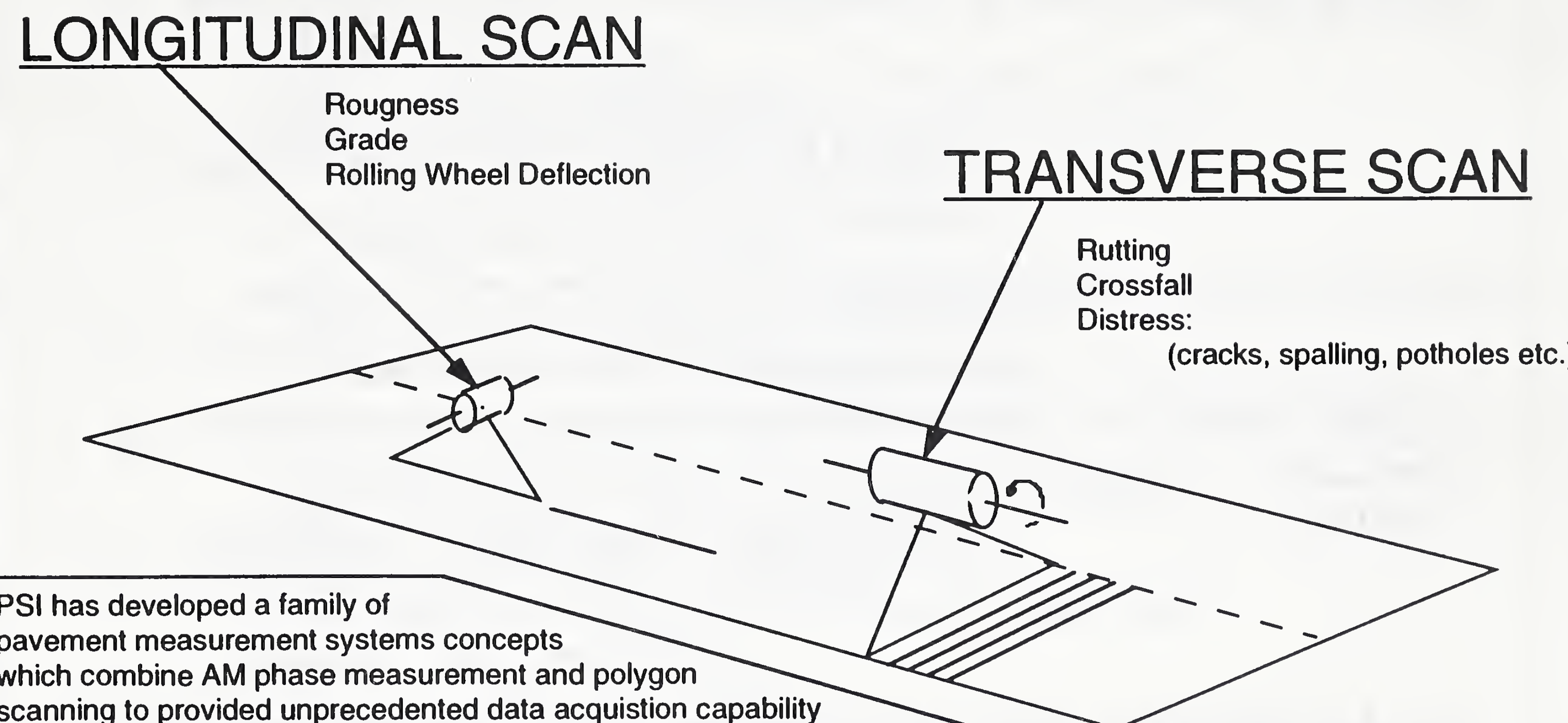
SCANNER ORIENTATION



PSI has developed a family of pavement measurement systems concepts which combine AM phase measurement and polygon scanning to provided unprecedented data acquistion capability for pavements. Detailed design and testing are underway for specific applications. PSI has applied for patents on these system inventions.

- PATENT APPLIED FOR -

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PAVEMENT APPLICATIONS SUMMARY

- Transverse Profile
  - Wheel rutting, crossfall, overlay/grinding design (Maine DOT)
- Distress (Potholes, cracks etc.)
  - Robust real-time automatic processing viable (vs. imaging)
- Longitudinal Profile (Roughness)
  - Potential to extend maximum wavelengths: Grade
  - Precise direct measurement of short wavelengths
  - Suitable for new wet pavement QC & Machine control
  - Degree of compaction of sub layers and asphalt
- Deflection from Rolling Wheel
  - Eliminate need for stopping traffic
  - Realistic rolling wheel load
- 3D Topography (Longitudinal & transverse scan)
  - Survey and preparation (land or aerial vehicle)
  - Rehabilitation and replacement
  - Robotic Automation

PATENT APPLIED FOR

- PATENT APPLIED FOR -

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STATUS

- TECHNOLOGY
  - Electro-optics: Bandwidth and Precision Proven
  - Ongoing efforts with low-speed robotic sensors
    - SHRP Automated Pothole repair
    - Darpa ALV, bin picking
  - Model, Systems Engineering and Patent Application Complete
- PROGRAM INITIATED
  - Plan: Model, Breadboard, Model Validation, Design and Test
  - Schedule: 1.5-3 years
  - Detailed design and testing underway
- FOREIGN COMPETITION
  - Japan: Komatsu, Pasco
  - Sweden: IMS RST & RDT
  - UK: WDM Ltd.

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BRIDGES AND STRUCTURES

> The scanned laser topology measurement technology being developed by PSI can be applied in many areas beyond pavements. This brief summary was provided to address the broader interest of the NSF workshop.

- REQUIREMENTS
  - Verify integrity
  - Identify and rate corrosion severity
- CURRENT PRACTICE
  - Manual visualization
- MODERNIZATION STATUS
  - Aerial and Manipulator Robotic Video Deployment
  - Laser site line warning system
- OPTICAL RANGE SCANNING POTENTIAL
  - Robotic deployed
  - Surface topography to rate corrosion severity
  - Macro-topography to measure structural geometry

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