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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
Ronald H. Brown, Secretary

TECHNOLOGY ADMINISTRATION
Mary L. Good, Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Arati Prabhakar, Director

FINAL REPORT

VOLUME: 4

To:
FEDERAL HIGHWAY ADMINISTRATION

Prepared by:

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Dr. Ernest Kent

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FOR POTENTIAL RESEARCH EFFORTS

SITE INTEGRATION PROPOSAL

TO:

FEDERAL HIGHWAY ADMINISTRATION

BY:

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
ROBOT SYSTEMS DIVISION

SEPTEMBER 28, 1993

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Site Integration Through Hierarchical Control

R. Lumia, Robot Systems Division, NIST
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1. Goal

The goal of this work is to reduce construction time by half through the use of hierarchical control for the integration of all activities at the worksite. It will accomplish this through:

1) Automating planning and scheduling directly from databases of project planners, design engineers, contractors, and materials suppliers.

2) Generating detailed plans directly from automated survey data.

3) Increasing the efficiency with which men and machines are used by ensuring that all necessary tools, materials, and personnel are available at the proper places and times.

4) Optimally rescheduling use of men and machines in real-time in response to short-term disruptions caused by weather, equipment malfunction and similar unpredictable events.

5) Eliminating time spent searching for materials by automatically tracking and controlling materials delivery and storage.

6) Increasing the efficiency of machinery operators by providing them with exact visual guidance for earth removal, materials placement, and site-positioning.

7) Reducing re-work by enhancing the accuracy of siting, placing, cutting, and forming operations, controlling materials flows, and by directly guiding work from master plans and designs in real-time.

8) Acquiring as-built information as the work occurs to reduce turn-around time for checking and correcting operations.

In addition to reducing construction time, the proposed work will reduce materials costs by reducing waste, and enhance safety by monitoring equipment in motion.

2. Background

2.1. Root of the problem

It is well known that unforeseen events can idle equipment at the worksite, which wastes time and costs money. A traffic jam can result in the rejection of a cement delivery. Overnight rain can fill a hole and work cannot proceed until a pump arrives. An event can occur which requires equipment not at the worksite. Normally, it is the job of the site foreman to deal with these events. Our argument, however, is that the foreman can only oversee his "island" of activity and therefore is implementing a local rather than global optimization of a construction plan. The foreman's fundamental limitation is that he lacks information about what is happening at the other worksites of the project. Consequently, *the key problems are the lack of global information and a method for using* *it effectively.*

A site foreman does an excellent job in allocating resources at his worksite, i.e., he does the best job he can with the information he has. However, this local optimization results in sub-optimal use of equipment, sub-optimal planning for materials delivery, sub-optimal use of personnel. Theoretically, if the foreman knew about the state of all of the project worksites, resources could be allocated more effectively. However, in practice, the foreman would drown in the details. He needs tools to help him sort out the complexity in order to enhance his performance. Hierarchically organized control systems address this issue of complexity and provide a tool to make construction sites more efficient.

2.2. Advantages and applications of hierarchical control

Hierarchical control is not a new idea. It was practiced in China around 3000 B.C. It is commonly found in the military, and most business and government organizations. Recently, these concepts have been applied to controlling machines. Hierarchical control has been used for many systems including

- Factory control in an automated manufacturing research facility at NIST
- Factory workstation control
- Machine tool loading and unloading
- Robotic deburring
- Advanced controller for machine tools, robots, and coordinate measuring machines
- Advanced inspection system
- Vision-guided robot manipulation
- Vision-based automated highway driving
- Unmanned land and undersea vehicles
- Submarine operation automation
- Coal mine automation
- Space Station telerobotic servicer
- Robot crane

While this set of applications may appear disparate, the common thread is that complex systems require coordinated activities in order to achieve optimal performance. We argue that construction sites are also complex systems, and therefore are amenable to hierarchical control techniques.

3. Hierarchical Control for Site Integration

3.1. Hierarchical control overview

A hierarchical control architecture can integrate many people and machines into a coordinated system. It forms the "glue" which connects measurement technologies and equipment in order to enhance performance while reducing time and waste. A good hierarchical control system should provide an engineering methodology for the design and implementation of the system. It should define how global plans can be decomposed into local actions that can be executed by production equipment. Also, it should allow any amount of automation, i.e., it should support the entire range from teleoperation to autonomy, in its attempt to balance cost and performance. This is possible because hierarchical control systems deal with planning horizons ranging from years and months, down to jobs lasting weeks, days, and hours, as well as for tasks lasting minutes, seconds, and even milliseconds.

Some of the elements of a hierarchical control system architecture and how they pertain to site integration are shown in Figure 1. There are three parallel hierarchies: task decomposition, world modeling, and sensory processing. Task decomposition, as its name suggests, decomposes a task into smaller and smaller subtasks, eventually culminating in commands sent to the equipment. The world model stores a representation of the worksite. Sensory processing collects and analyzes data to keep the models in the world model in registration with reality.

Figure 1 also introduces the concept of multiple levels of control, only two of which are shown in the figure. Each level's planning horizon is roughly 10 times longer than the level below it. For example, the task decomposition box performing the strategic long-term plan could be planning a day's worth of activities while the level below is concerned with a sequence of tasks which require 15 minutes each. At the lowest level, the world model maintains an up to date model of the site, e.g., the site model could be concerned with the functionality of the equipment, precisely where each piece of equipment is and what it is doing, and the current state of the task executing. At a higher level, where the time frames are more broad, the world model could store the CAD model of the road, the desired end product, as well as the as-built model, the reality of the constructed road. Similarly, sensor processing tasks could be divided between short time frames, e.g., gathering specific road measurements for a small part of the road, and longer time frames, e.g., integrating those short term measurements into a global measurement for longer road segments.

In applying hierarchical control to various applications, there is significant flexibility in choosing appropriate sensors, planners, etc., and configuring these components into a real-time control system to achieve any desired level of automation. The same approach applies to site integration by implementing the system in phases and demonstrating the value added for each phase.

Figure 2 shows how the real-time planner at the lowest level of the architecture would be used to coordinate construction equipment. Any desired level of automation is possible. For example, the system could simply provide instructions to the human operators of the equipment. Alternatively, it could use the human operator to control the location of the vehicle but automatically control the remainder of the equipment processes. The most sophisticated alternative would be to control the entire operation autonomously, which may be technologically possible but is probably too costly at the present time. In a similar fashion, Figure 3 shows how sensors could be connected and configured into a real-time system. Figures 4, 5, and 6 show more detail of a potential implementation of the hierarchy with different proportions of autonomy.

3.2. Stages of integration

Hierarchical control allows technology to be integrated in phases. For example, the output of the real-time planner in Figure 1, which connects to equipment, can take different forms depending on the state of technology. In the short term, the output could be a screen with instructions to the foreman and equipment operators. More advanced technology provides the operator with the CAD design superimposed and registered with the worksite. Using this graphics display, the operator could place structural materials, forms, etc. As graphics technology advances, virtual reality techniques can be incorporated. Ultimately, the commands could control the equipment directly with no human interaction.

To illustrate the sensory side of Figure 1, consider the following scenario. Truck 65 has arrived with shipment 16 and is supposed to dump its contents at the worksite. In the short term, the fact that truck 65 has arrived with shipment 16 is keyed manually into the system. The system responds with the instruction to dump contents at grid 87. Then, the truck driver views a display which informs him where he is, so that he can determine how to reach grid 87 exactly. As technology advances, the system could take control of the vehicle once it enters the worksite, automatically access the database to determine the desired location, drive the truck to that place, and control the dumping. In all cases, the system would automatically update the site model of the material database.

Consider another technology. If materials are bar-coded, the materials database can be updated every time material is moved from one location to another. Inventories can be adjusted, and orders generated automatically. Keeping track of the location of objects at the worksite goes beyond monitoring materials.

Position sensors can determine the precise location of equipment during operations at the worksite. For example, it is possible to measure the location of the backhoe bucket in real-time. This information can be used to update the site database in real-time, which ultimate instructs the operator precisely where and how to dig.

Laser surveying instruments are commercially available to build CAD models of the terrain. This information needs to be incorporated into the hierarchical control system to guide the crews and equipment operators. Ultimately, when updated by input from the field, these data can be used to create the as-built model of the site.

4. Scheduling activities at the worksite

A road construction project may be thought of as a set of large-scale tasks, such as excavation, grading, paving, bridge construction, etc., which must be carried out in a special order to accomplish the final construction goal. The execution of these tasks requires the careful coordination of resources delivered to and removed from the site, the availability of machines and people at particular places and times, and the arrangement and transport of parts and materials within the worksite. While many different factors affect the success of such a project, the design itself and the mapping of that design into a project plan are critical to the efficient management and resulting quality. Computer-based aids for the development and tracking of complex projects offer fundamental advantages to the road construction industry where coordination of multiple activities on a preset schedule is vital to efficient and safe operation.

Computer-based design tools are now required by many states for large highway construction projects. In this approach, the designer develops a representation of his highway project design as a computer-based (CAD) file, and can use that file as a basis for structural analysis, materials selection, project costing, environmental impact, and graphics rendering for presentation. The design itself provides the common core, and the computer representation enforces a consistency among the various types of analysis. Such techniques are commercially available and increasingly used for major projects. A CAD-based design and database representation will be an essential component of the proposed demonstration project.

While the current CAD tools provide useful means to capture the basic design of the construction project, there are many additional ways in which this representation may used for project coordination and management. Current CAD design methods are used in the preliminary costing and assessment of projects, but are not commonly used in the planning and operations themselves. We propose to bring the CAD design into the project planning and day-to-day management of the project in order to increase the efficiency and accuracy of these operations. One example of this use is the site layout problem. The CAD tools should be developed to represent a sequence of construction phases depicting the spatial configuration of partially completed work. Then, the layout of materials stores, equipment, and personnel may be configured to maximize the efficiency of the workplace. Minimizing the transport and relocation of materials achieves a significant gain in operations efficiency.

A second example of the integration of CAD tools into road construction operations, is the automated site positioning system. The CAD representation specifies the position, location, and shape of objects and surfaces in three-dimensions from the design. For example, the location, grade, and shaping of the final road surface is exactly specified. However, in practice, it is extremely difficult to map this specification onto a work site. Surveying, marking, and remarking of positions, elevations, and grades is a routine practice during road construction. Maintaining accuracy throughout the many steps which are required is a major task. An automated site location system provides a means to locate exact positions and orientations of objects in the three-dimensional workspace. A given machine, such as a bulldozer, would be tracked by beacons on the site, and its position and velocity would be monitored and displayed. Such systems are now under experimental development and demonstration of the integration of such a site location system with CAD specifications would be a major focus of the proposed demonstration project.

Given a project design which can be linked into the operations of the project, there are enormous opportunities to improve the task planning and scheduling for the project. There are already some existing tools which are used in road construction project planning. PERT (Program Evaluation and Review Technique) charts and CPM (Critical Path Methods) are the most common. These methods provide a means to evaluate alternative sequences of tasks within a complex project, assign costs or penalties to different tasks, and choose which sequences are best suited to the given project. In these approaches, planning is the process of choosing the order of work among the tasks and is usually shown as a linked series of nodes in the CPM diagram. Scheduling is the assignment of times, or time bounds, on these tasks and is used to estimate the overall completion time and the critical times for availability of resources. While these methods have provided important advances in the systematic approach to project planning, they have two principal deficiencies: (1). lack of embedded knowledge, and (2). lack of adaptive or dynamic behavior. These two deficiencies may be addressed by additional new developments in planning methods.

PERT and CPM do not embed design information or knowledge of the domain into the planning process. The formulation of the plan usually relies entirely on the skill and experience of the human planner to assess and assimilate the many variable which affect the planned sequence and its variability. The development of knowledge-based planning systems addresses this issue and has resulted in prototype programs which provide improved planning environments for specific domains. In our work on this demonstration project, we would emphasize the development and demonstration of two specific systems: First, a knowledge-based site layout system which would assist in the placement of materials and machines and the optimal configuration of the site for improved efficiency and safety. Second, a knowledge-based scheduling system which would optimize the utilization of machines and personnel based on internal representation of domain knowledge about the needs and constraints of the road construction domain. Incorporation of these tools will have a direct benefit to the efficiency of the project, the utilization of equipment and facilities, and the ability to monitor and assess progress.

A PERT or CPM analysis is usually done prior to the project and is difficult to change or update as unexpected events occur during the course of the project. This lack of adaptive or dynamic behavior often renders the original plan useless within a short period after the project commences. Instead, new tools are required which can respond to perturbations in the constraints of the plan, or dynamically replan successive tasks as necessary during the project. Such tools in effect become a top level of coordination for the principal tasks and provide a basis for the hierarchical decomposition of subtasks. These discrete-event modeling and control methods have been used extensively in the manufacturing domain where dynamic changes in requirements and resources require frequent revision of manufacturing plans. In the case of road construction, a "discrete-event" may be thought of as a specific task with well-defined start time and end time. Each such task has certain resources which are required. For example, a trenching and pipe-laying operation may require the availability of an excavator, a crane, a compactor, and the next section of pipe. The availability of these 'preconditions' to an event define a state of the system model and enable the execution of the event itself. The outcome of the event is a new set of state conditions.

A powerful set of models which represent these conditions and actions very effectively are called Petri nets. The Petri net uses a circle, or 'node', to represent the state of a resource, and a line with arrows, or 'transition', to represent the execution of an action ('firing of a transition'). Figure 7 illustrates this notation for Petri net models, and a sample Petri net model for the trenching and pipelaying problem is shown in Figure 8. In this example the crane is a resource which is shared by two subtasks, setting the new pipe section and placing the compactor in the trench. Mediating a shared resource in this fashion and coordinating parallel operations are particular strengths of the Petri net representation. It is important to recognize that this type of model represents a set of possible plans, rather than just one plan. All of the possible plans are consistent with the constraints of the problem, but may be initiated by different events. Thus the Petri net is inherently a dynamic model capable of responding to different conditions as the arise. In addition, we can attribute estimated execution times to different transitions and assess the alternative execution time of the whole task depending on different possible conditions which may arise. We thus assess the range of possible outcomes and incorporate that into our planning process. Responding efficiently to these 'what if?' questions in the planning domain is a key attribute of the Petri net modeling approach, and will provide a basis for coordination and control of discrete event sequences during execution of the project. Existing software tools are available which can be adopted to the demonstration project and would provide a framework for modeling and planning at the discrete-event level. As described below, further decomposition of tasks results in a hierarchy of continuous control modes which can be systematically organized as a hierarchical control system.

Implementation of the coordination and control functions in a complex work environment such as a construction site will require attention to communications and information transmission capabilities. A construction worksite may be thought of as a network of users and machines, each with different elements of the overall task. However, the coordination of these various functions will require that common elements, like the project design, by available and consistent for all of these users. In addition, as different aspects of the job proceed, it is necessary for the status of jobs to updated and communicated to other parts of the worksite. Such a distributed user community constitutes a network, and the definition and implementation of networking principles for a highway construction worksite will be a major component of the proposed demonstration project. This network will require agreed upon modes of transmission on information as well as establishment of protocols, or standards, for relay of information. For example, representation of the grade of the road in the design database might be transmitted to the grader control system in one form, but accessed by the pavement compaction inspection system in another form. These interactions must be specified and enforced in order to assure consistency among the different agents in the network system.

For the road construction site, many of the elements of the network will be machines which are concurrently carrying out real-time tasks. This real-time distributed interaction imposes still another requirement on the design of the system. A standard for communications among the real-time elements of the system must be adopted, and must take into account the timing of the individual processes and their interactions. This requirement for a real-time distributed operating system to coordinate processes is common to many other systems which integrate computers in an interactive domain. One approach to this problem utilizes a message-passing protocol which permits computers to communicate through messages which update the timing requirements and constraints from each of the other systems. The integration of a discrete-event control model, such as the Petri net, with a real-time distributed operating system provides the framework for implementation of communications and coordination of multiple tasks in the road construction demonstration project. Individual or hierarchies of continuous controllers, sensors, and modeling systems which control the motions of individual machines act as nodes on this communications network and report their status and functions through the distributed operating system mechanisms.

5. Benefits of using hierarchical control

Hierarchical control can help address the root cause of non-optimality at worksites: lack of global information and an effective way to use it. The following table lists a particular capability which can be achieved with a hierarchical control system, whether the time frame for its implementation is considered short term (1-3 years), medium term (3-5 years), or long term (5-10 years), and a specific example of that capability applied to site integration. The benefits of using hierarchical control transcend the list, and therefore this list should be considered to be representative of the types of benefits one should expect.

Table 1: Productivity improvement through hierarchical control

CAPABILITY	TIME FRAME	EXAMPLE
Efficient scheduling based on variable work-site conditions	Short	When equipment breaks, a plan can be generated to optimize work for the entire site by transferring equipment from one work site to another.

Table 1: Productivity improvement through hierarchical control

CAPABILITY	TIME FRAME	EXAMPLE
	Short	By having an up to date schedule based on the actual state of the sites, people are sent to sites when needed to perform specific tasks, thereby minimizing idle time.
	Short	A weather report of overnight rain will automatically generate scheduling of pumps to arrive at sites where holes were previously dug.
	Short	Material delivery schedules and equipment use plans can be re-generated in real-time and reflect the most up to date information available about the worksite.
Reduce time to locate equipment or materials	Short	When equipment breaks, or the state of the site changes, new equipment may be necessary. The system can request the "best" equipment automatically by balancing the work done at one particular site with the work in progress at all other sites.
	Short	When new equipment is needed for a site, all of the parts can located quickly, e.g., a pump must arrive with hoses and the proper couplings in order for it to be useful.
Real-time location of all equipment registered with CAD design of site	Medium	By knowing the precise location of equipment with respect to the design, time can be saved in many tasks, e.g., compact the area around lane joints to a greater extent than the remainder of the road surface.
Survey integrated with plan from highway department	Short	Moment by moment guidance can be sent to operators of equipment to enhance performance, e.g., graders minimize the removal of earth to achieve the goal in real-time.
	Short	Minimize rework resulting from errors in reading the blueprints for the site design. Measurements can be made (semi)automatically.
Timely distribution of design changes accessibly from design database	Short	Minimize rework due to changes in design.

Table 1: Productivity improvement through hierarchical control

CAPABILITY	TIME FRAME	EXAMPLE
Improve efficiency of interaction between man and equipment	Short	Moment by moment guidance and instructions to machine operators to prevent errors, and maximize quality of work. Operators can have complete information -- where, when, how much -- using inexpensive visual displays.
	Short	Operator of backhoe can use CAD model of location of various utilities by using real-time display of digging operations to avoid cutting through lines.
	Medium	Control system on backhoe prevents operator from digging into volumes occupied by utility lines.
Reduce time need for "cut and try" situations	Medium	Automatic calculation of the required dimensions for materials can be recomputed in real-time for "as-is" condition.
Improve efficiency of interaction between machine and machine	Short	Operator follows instructions on screen to perform mating of machine and its feeder.
	Medium	Operator drives feeder based on instructions but all other mating and feeding operations are automatic.
	Long	Machine controls all aspects of itself and its feeder, from requesting the time of feeding, to the actual coupling.
Automatic recovery of as-built databases	Medium	Minimizes cost and time if renovation is performed at site at some future time.
Increase safety	Medium	Sensors on machines monitor the state of the machine, detect errors, and shut down equipment in an orderly fashion when a dangerous situation occurs or a dangerous action is requested by the operator.

6. Summary

Hierarchical control lends itself to the organization of complex systems by providing the glue to connect myriad technologies into a coherent and understandable system. The concepts of hierarchical control were presented along with examples of specific benefits resulting from the technology.

The project described here will represent a demonstration of several major innovations in the integration of technologies for the planning, coordination, and control of activities on a highway construction site. The resulting improvements should fundamentally affect the way in which a construction project can be managed, and will result in more efficient use of manpower, equipment and materials, as well as increases in safety and quality of the project. The demonstration project will integrate a wide variety of technologies in a manner which demonstrates their utility. Many of these technologies will have substantial impact in themselves, and the incremental improvements which result from adaptation of specific individual innovations will be of substantial value. For example, improved knowledge-based planning tools will be valuable even with conventional worksite organization. Similarly, improved standards for CAD interfaces, and well-defined networking protocols for worksites will have substantial benefits in the gradual improvement of worksite technology.

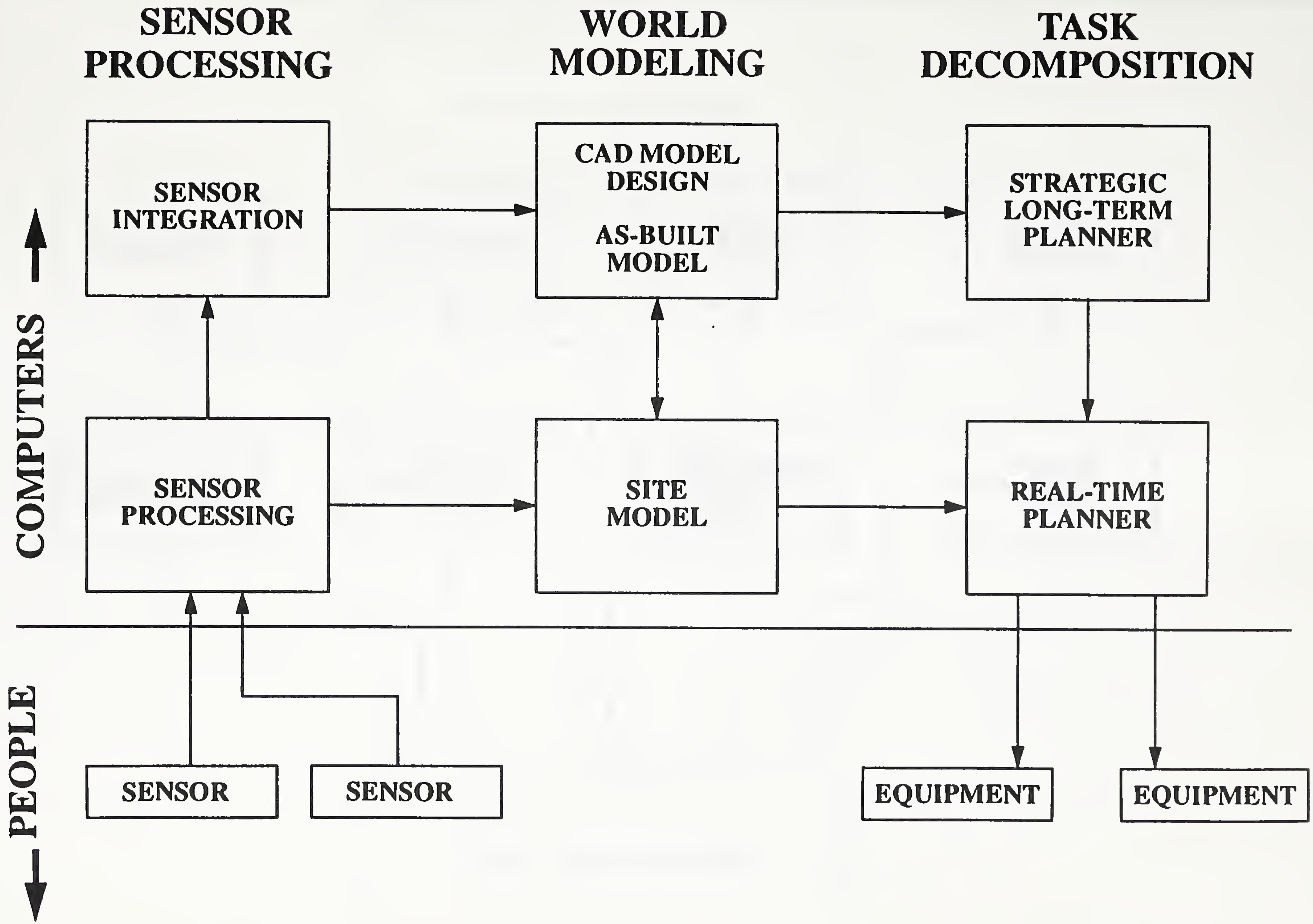


Figure 1. Elements of the RCS Architecture

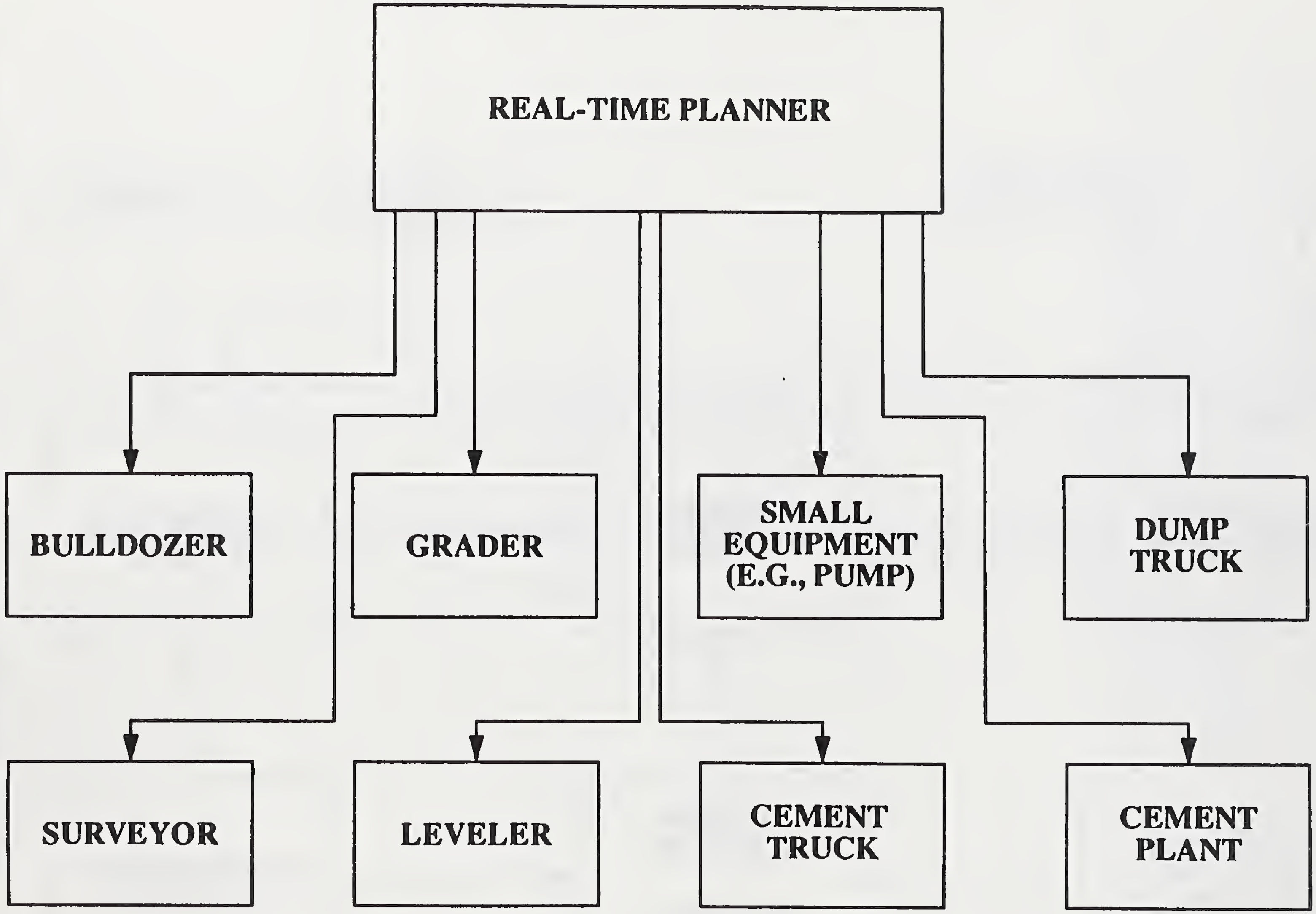


Figure 2. Equipment is Coordinated by the Real-Time Planner

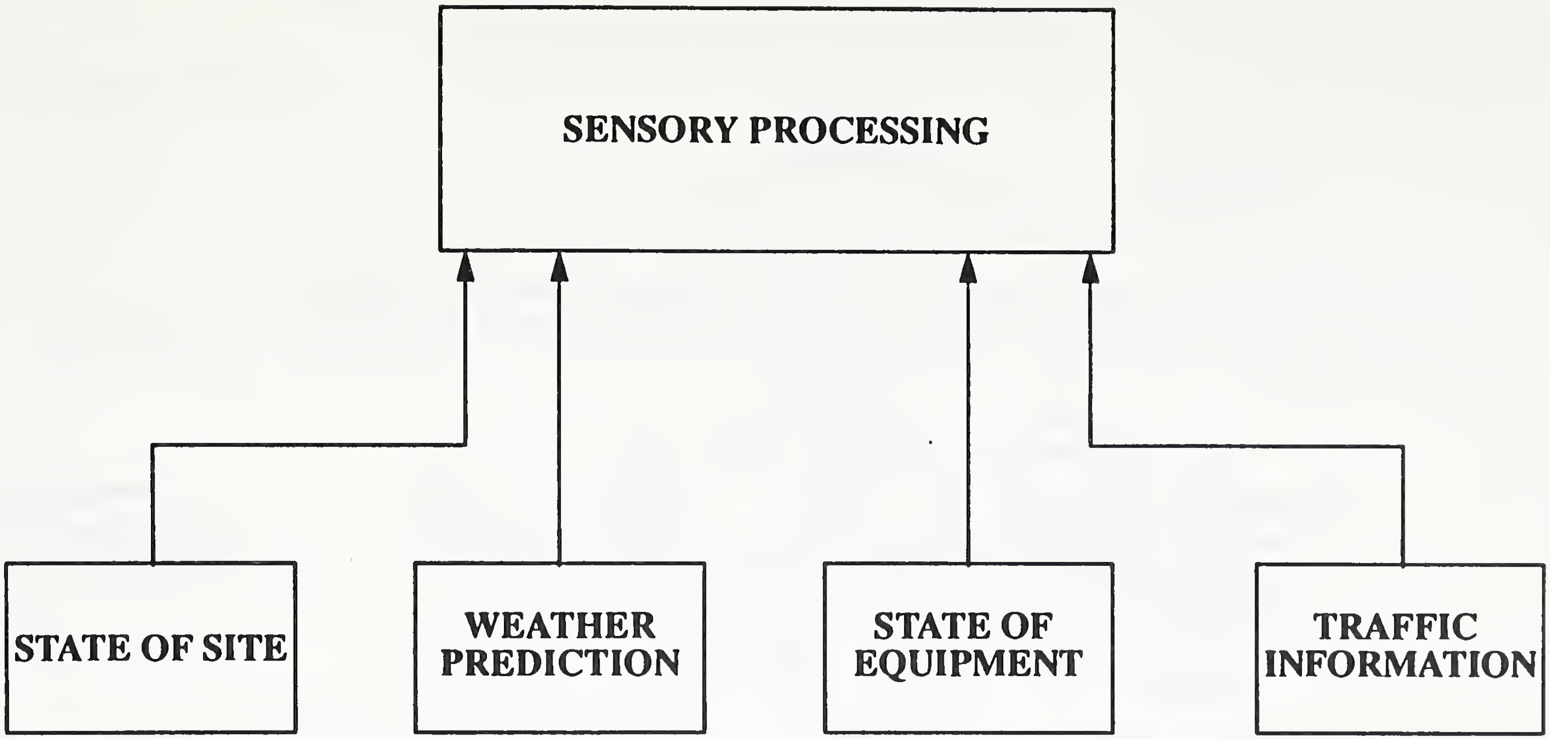


Figure 3. Sensing the Worksite

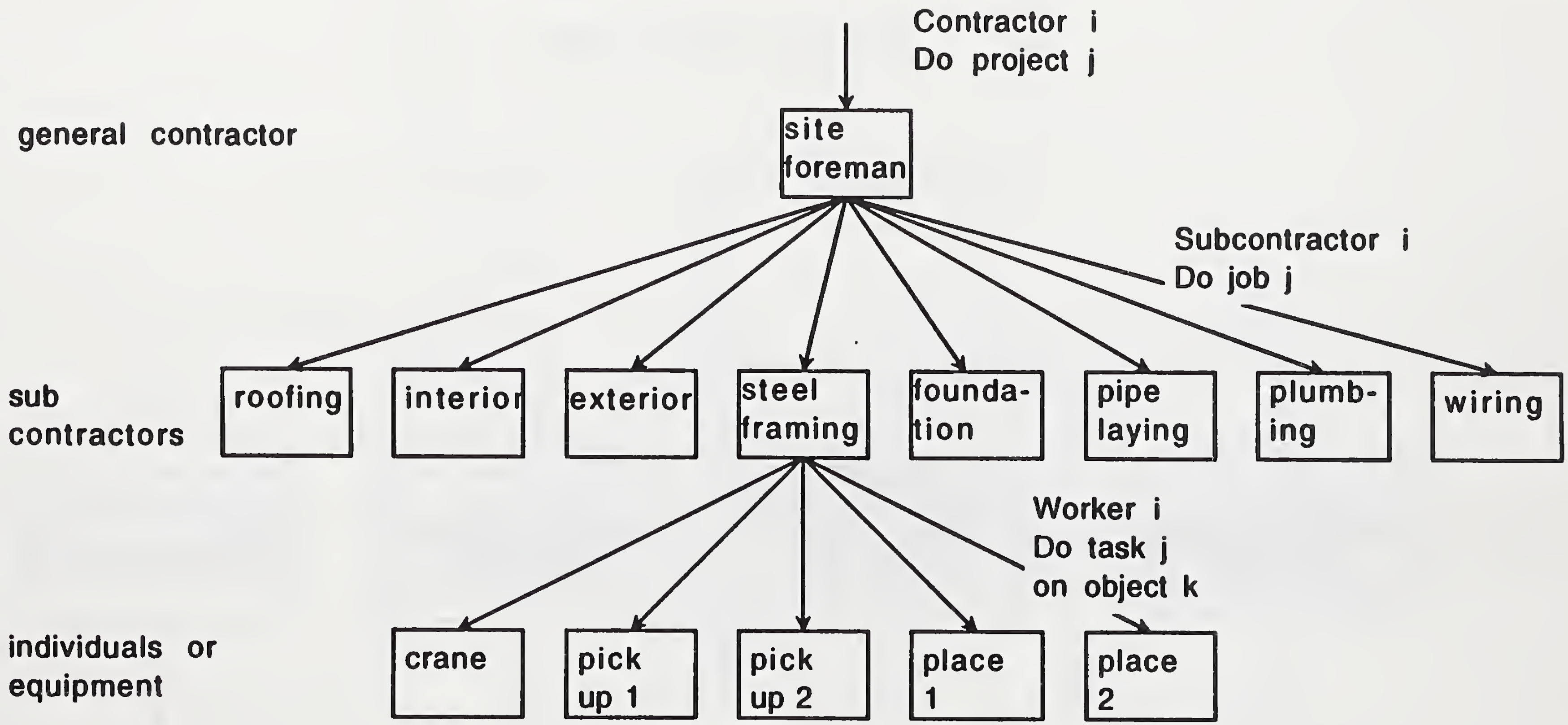


Figure 4. RCS for Site Integration - Instructions to Individuals

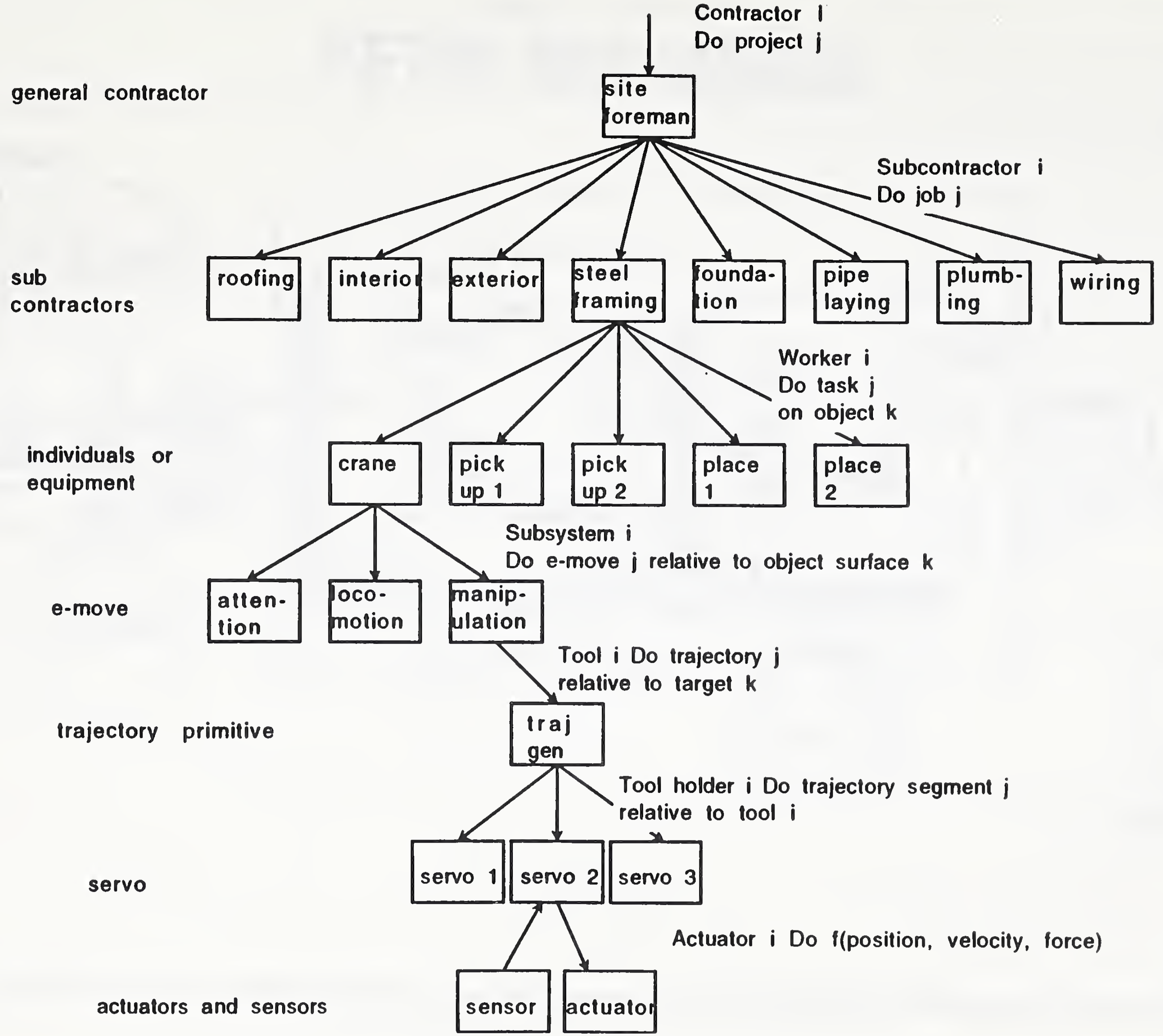


Figure 5. RCS for Site Integration - Total System

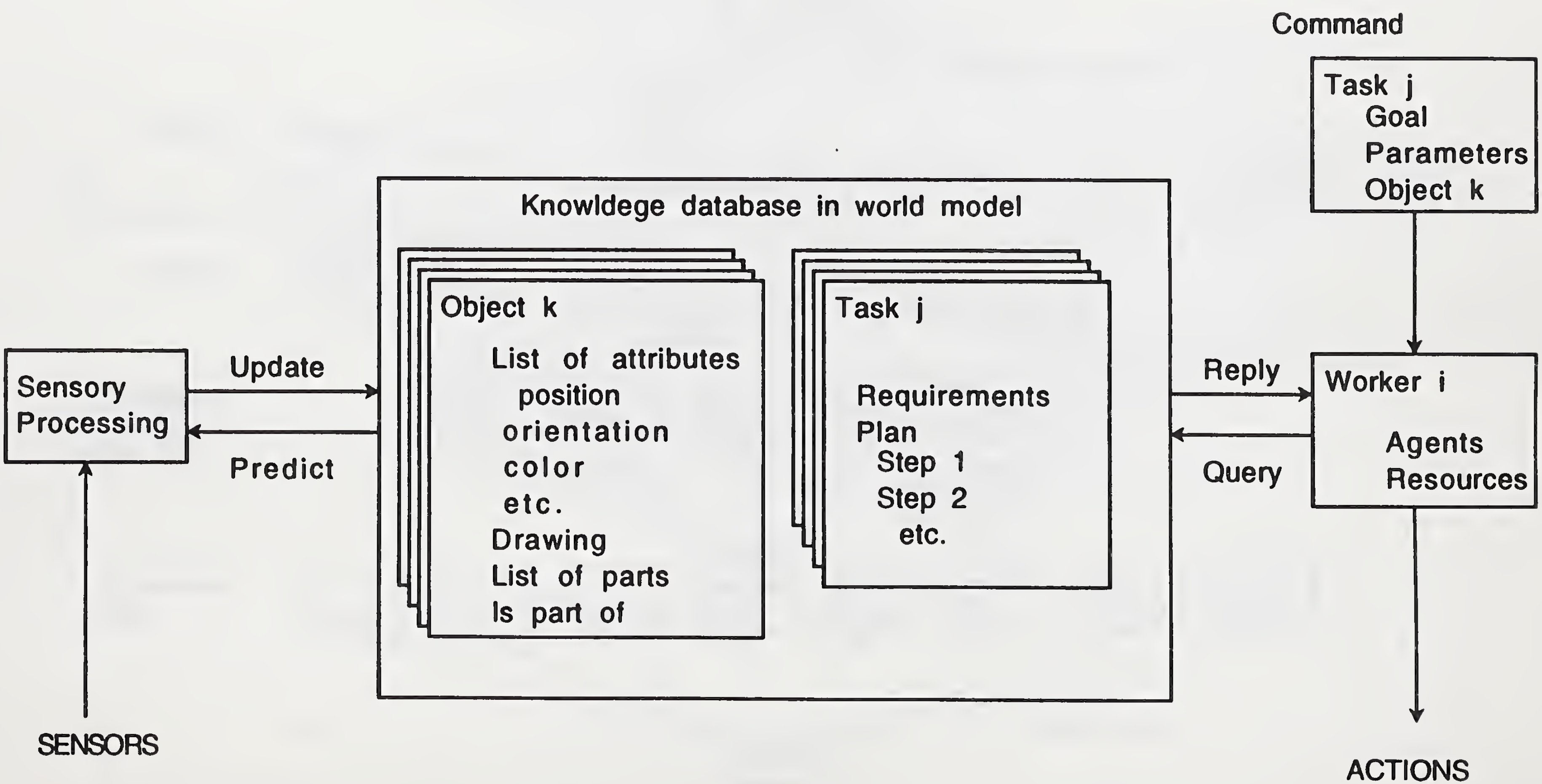


Figure 6. A RCS Node

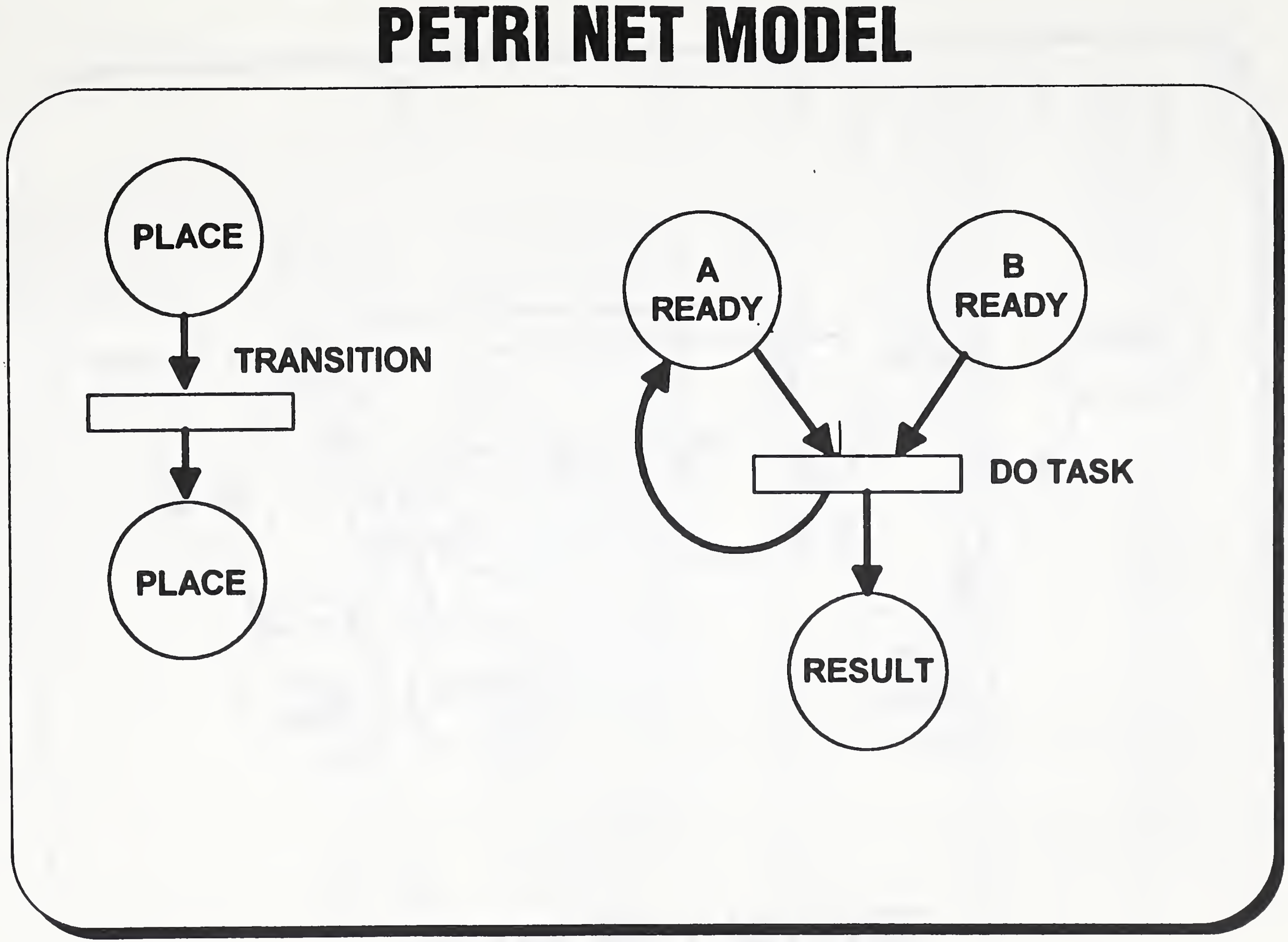


Figure 7. Petri Net Model Notation

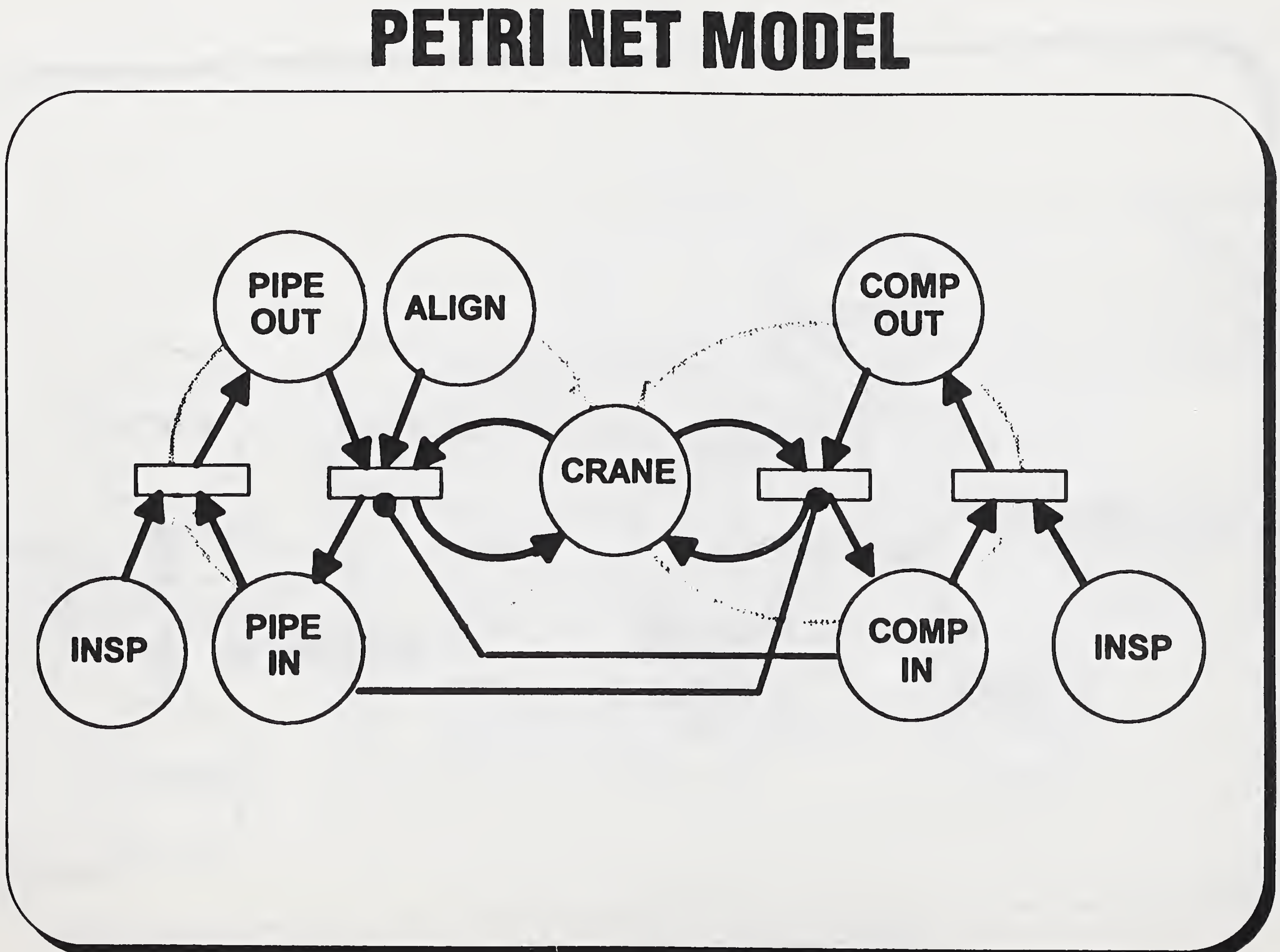


Figure 8. Petri Net Model for Trenching and Pipelaying

SITE INTEGRATION PROPOSAL
Outline and Deliverables

1. Objective

   The overall goal is to develop automated systems which will reduce construction time, reduce costs, improve efficiency and productivity, and enhance quality.

2. Approach

   Site-integration management systems will be developed which will integrate construction databases and CAD designs with interactive planning and scheduling, and provide real-time control of on-site activities.

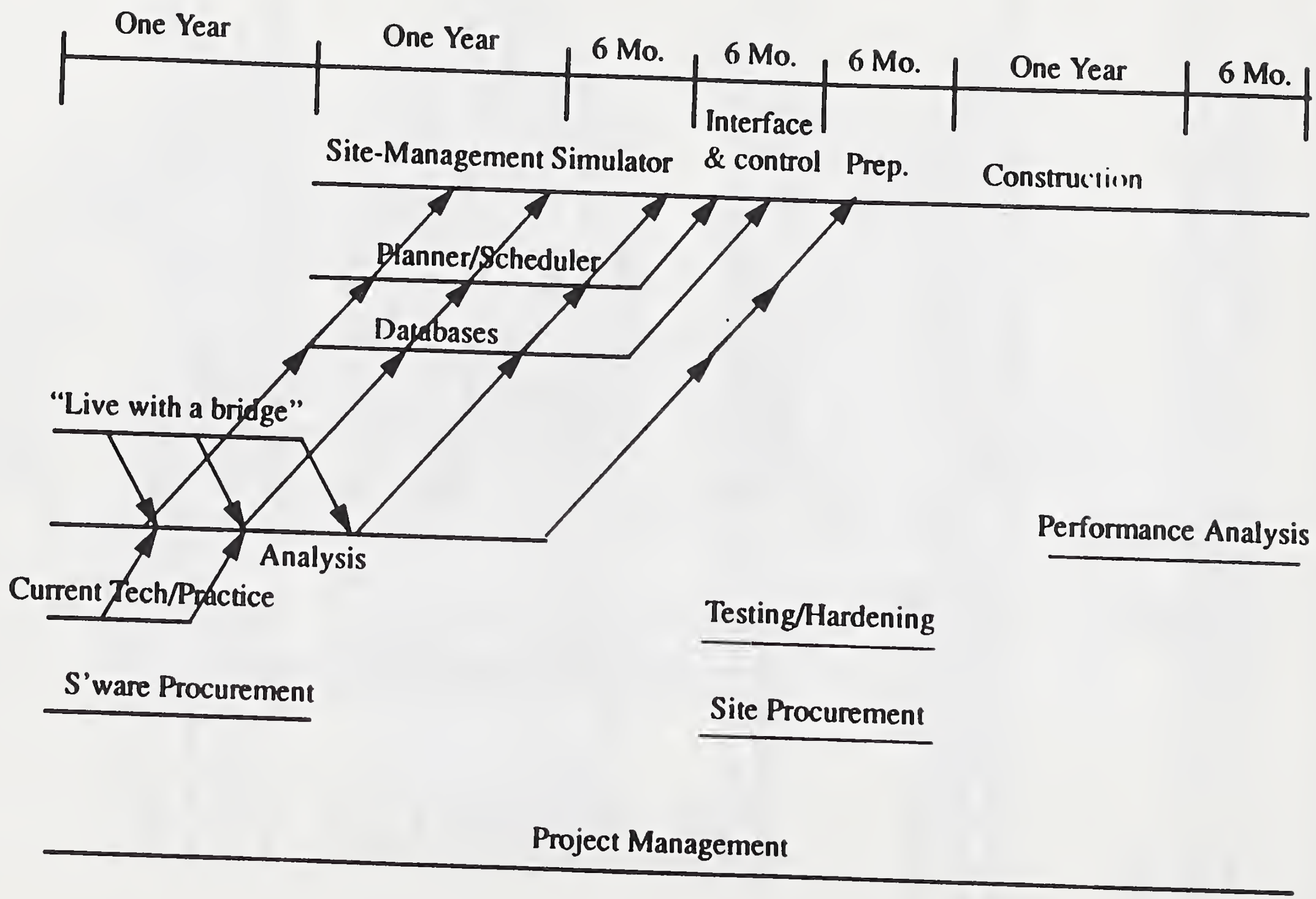
3. Deliverables

   Phase 1: An in-depth study of an example bridge-construction site, and plan for development of the site-management tools. Time: 1 Year.

   Phase 2: A site-management simulator with full plannin~ and scheduling capability, resource allocation, contingency handling, and site visualization. Construction managers and supervisors will be presented with all options and constraints and will be able to see consequences of alternative decisions on resource allocation, schedules, and subsequent alternatives. The state of the site at any point in time, under any set of decisions will be visible 3D displays.Time: 1.5 Years.

   Phase 3: Sensing and control interfaces will be added to the simulator enabling it to accept real-time site data and to interface to supervisors and equipment operators. This system will then be tested in construction of a bridge site comparable to the site studied in Phase 1. Time: 1 Year.

SITE INTEGRATION PROPOSAL
Timeline of Activities



SITE INTEGRATION PROPOSAL
Planning and Scheduling Activities

PLANNING - What needs to be done (activities) and how long will it take (activity time) with a given level of resource allocation (time, material, equipment, workforce).

SCHEDULING - When and in what sequence activities will be performed to satisfy dependence and constraints.

CONTROL - Monitor the execution of the activities and adjust the plan, schedule, and resource allocation to improve outcome.

SCHEDULE OF WORK

YEAR 1: Integrate database and graphical display of site operations with C P M activity network to visualize plans.
- Incorporate existing commercial CPM software
- Test and evaluate on phase 1 bridge study

YEAR 2:Integrate resource allocation tools into activity planning --interactively recommend alternative plans and visualize resulting operations and schedules.
- Utilize existing compiled data and guidelines where possible
- Analyze and incorporate results of the phase 1 bridge study
- Focus on recommendation of likely choices with interactive decision making rather than optimization and automated selection.

YEAR 3: Implement framework for integration of site data and monitoring to update plan and support decision making.
- Extend links of integrated database to update activities and states
- Develop mapping from activity network to Petri net model (use existing Petri net simulation and analysis software)
- Incorporate branching transitions and resource related preconditions
- Incorporate Petri net analysis tools for safeness, liveness boundedness

YEAR 4: Support bridge construction case study using integrated planning tools.
- Track plans and schedules versus execution of operations
- Conduct analysis of alternatives in parallel with execution
- Study and modify planner interfaces as the project proceeds.
- Summary and report on project -- evaluation of planner capabilities and impact on project outcome.

SITE INTEGRATION PROPOSAL
Simulator Prototype Activities

The purpose of the site integration simulator prototype is to store a representation of the worksite (the world model), to keep the representation current with processed sensor data, to interface the representation to application programs (GIS/ CAD/ planning/ scheduling), and to provide an interactive graphical user interface.

Tasks:

1. Establish functional requirements:

- survey bridge-building handbooks and guides
- review data gathered at bridge worksite
- identify construction site objects to be modelled
- identify characteristics of the objects to be modelled
- identify interactions between objects to be modelled
- identify RCS requirements

2. Select appropriate information technology:

- survey existing GIS/CAD systems and database development environments
- select system(s) to be used in prototype based on functional requirements

3. Design site integration simulator prototype:

- define conceptual objects/schemas
- define program interfaces to GIS/CAD systems and to planning and scheduling components
- define functionality of the interactive graphical user interface

4. Implement basic site integration simulator prototype:

- build database
- build interfaces to GIS/CAD application programs
- populate and test with data gathered at worksite

5. Implement planning and scheduling in the site integration simulator prototype:

- build interfaces to planning and scheduling components
- test by simulating observed worksite activities

6. Implement interactive graphical user interface:

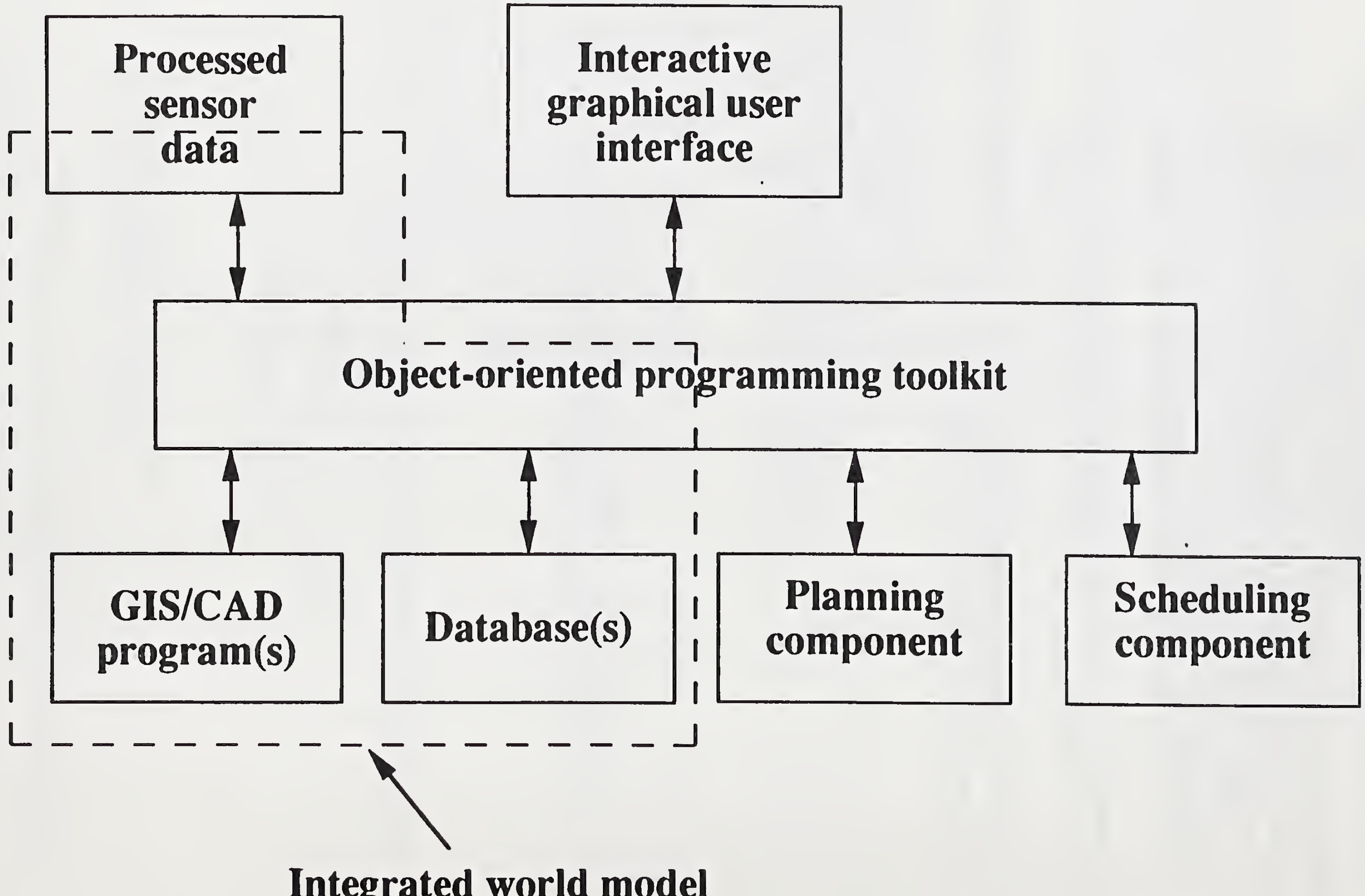
- build program elements that provide designed functionality
- test and modify interface based on in-lab experiments with engineering/construction personnel

7. Harden prototype and implement second bridge project.

The proposed manpower and funding for these tasks is 3 FTEs for the first three years at $450K/year, and 1 FTE for the fourth year at $150K.

At a minimum level of effort (150K), only task 1 and the first element of task 3 would be performed and a report would be issued.

Site Integration Simulator Prototype



SITE INTEGRATION PROPOSAL
Real-Time Control: Activities

Phase 1:

- Develop interfaces for RCS to support planning representation and command.

- Observe the bridge site. Study the ways an operator expects to use the system. Study sensing problems.

- Plan implementation of RCS instantiation and coordinate with planning and database system to ensure compatibility.

Phase 2:

- Implement RCS installation and integrate it with simulation capabilities.

- Implement prototype operator interface system.

- Develop operator interface screens for different modes of operation.

- Experiment with integration of commercially available measurement and sensor systems .

Phase 3:

- Harden implementation of RCS and test thoroughly.

- Support operations during bridge construction.

- Analyze performance.

SITE INTEGRATION PROPOSAL
Schedule of On-Site Events

Bridge-site Observation Phase.

One technical worker would be assigned to "live with" the bridge. He would spend essentially full time on site. His duties would be to become fully familiar with all phases of the construction process so that he could subsequently serve as a resource to the scientific team developing the site integration tools. He would require the cooperation of the supervisors and workers on the site to answer questions and explain procedures, but would be instructed to minimize interference with ongoing activities. He would need to be able to videotape operations for later review by project scientists. He would need on occasion to set up tests of sensing equipment to study the performance of different sensors under site conditions. Also, runs of data from sensors would be required to serve as simulated input during later development of the computer programs. Other technical staff from the cooperating scientific groups would need to visit the site to see specific things. The on-site technical worker would be responsible for arranging their visits to coincide with the work to be observed, and for setting up any special tests needed for their visits. In general no significant interference with construction personnel or equipment is foreseen. A small van would be provided to house all equipment, and any sensors placed on equipment or in work areas would be small and would be fully cleared with operators and supervisors before installation.

Bridge Construction Phase.

After development of the site-integration tools and installation of the sensors at the test site, we would expect the following scenario.
All materials entering the site and moving within the site would be tracked by the system through the use of GPS/GIS technology and other sensors. The system would employ site-planning and resource allocation techniques to specify the optimal placement of materials and timing and routing of materials. The current state of the site and the expected future state at any time could be viewed by supervisory or management personnel in 3D displays with color-coded indication of status of completion. As-built databases would be automatically generated, and any differences between planned and as-built status would be highlighted. Management decisions would be translated into schedules for supervisors' which would be coordinated to achieve optimal efficiency in use of crews and equipment. Contingencies such as weather or machinery breakdown that forced changes in scheduling would be accepted by the system. It would then give managers and supervisors a display of the scheduling consequences, and plans for optimal ways to change the work schedule.

SITE INTEGRATION PROPOSAL
Proposed Costs By Year

Time Schedule:

On-site study of first bridge construction	1.0 yr.
Construction of database and simulator	1.5 yr.
Interface to sensor and control systems	0.5 yr.
	3.0 yr.
Hardening and testing while waiting for 2nd site to commence construction.	0.0 to 0.5 yr.
	0.0 to 0.5 yr.
Test integration of 2nd bridge construction	1.0 yr.
Study and analysis of results	0.5 yr.
	1.5 yr.
Total time	4.5 to 5.0 yrs.

Budget, year one:

Manpower, fully loaded

RPI 0.2 faculty, 0.5 graduate student	75k
BFRL 0.5 FTE staff	75k
RSD 0.5 FTE staff	75k
On-site staff plus expenses and support	225k
	450k
Technology assessment study	25k
Project management and software	25k
	50k
Total, year one:	500k

Budget, year two:

Manpower, fully loaded

RPI 0.5 faculty, 3.0 graduate students	230k
BFRL 3.0 FTE staff	450k
RSD 2.0 FTE staff	300k
	98Ok
Project management	100k
Software	150k
	25Ok
Total, Year Two:	1230k
Budget, year three:	
Manpower, fully loaded	300k
BFRL 2.0 FTE staff	500k
RSD 5.0 FTE staff (2.0 full-time on site)	225k
	1025k
Project management	100k
Terminals, networks, interfaces, sensors	250k
Field testing and hardening	75k
	425k
Total, year three:	145Ok

Six month period
(Allowed for synchronization
with 2nd bridge project (Est.) and additional
preparation as indicated.)

Site setup	25k
Field testing/hardening	75k
Total	100k

Budget, year four:

Manpower, fully loaded

RPI 0.2 Faculty, 1.0 Graduate Student	150k
BFRL 1.0 FTE Staff	150k
RSD 1.0 On-site staff + support	230k
Project Management and travel	100k

Total, year four	630k

Budget, Six-months of final analysis

Analysis of results	100k
Management, report preparation	25k
Total	125k

AUTOMATING PAVEMENT DISTRESS ASSESSMENT USING MORPHOLOGICAL IMAGE ANALYSIS

by

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Table of Contents

1. SUMMARY

Distress assessment is an essential component of pavement management systems. The objectives of distress assessment are to evaluate the performance of pavement structures, monitor pavement condition over time and to formulate appropriate maintenance programs.

There are no standard procedures for conducting distress surveys at the current time. These methods involve a significant manual component that results in a number of problems, such as non-repeatability, subjectivity and high personnel costs. Consequently, it has been recognized that automating distress surveys using image analysis is of great significance in objectively evaluating the distresses.

The present study addresses the development of a computerized system for automating distress data based on mathematical morphology that uses the texture present on the pavement surfaces to analyze cracking as well as other forms of distresses. The goal of the proposed study is to develop and refine morphology-based image analysis algorithms, and evaluate the feasibility of applying this computerized technology to the automation of pavement distress surveys. Findings will be based on the ability of the developed image processing technique to identify distress types and severities on the photographs of asphalt and concrete pavement surfaces.

A significant feature of the morphological approach is that distresses other than cracking may also be detected and quantified. Another major feature of the proposed study is that it does not involve the development of different algorithms to detect and quantify different distresses. The development of a unified approach to handle different types of distresses under different conditions leads to a significant computational advantage. Finally, the current approach is capable of performing well on a number of different pavement surfaces, including those that exhibit extensive texture. Unlike other existing approaches, the current algorithm utilizes texture information and, therefore, is more robust in the presence of pavement texture.

2. INTRODUCTION

Distress assessment is an essential component of pavement management systems. The objectives of distress assessment are to evaluate the performance of pavement structures, monitor pavement condition over time and to formulate appropriate maintenance programs. The goal of the proposed research effort is to study the feasibility of automating pavement distress surveys and the development of a computerized image processing system for conducting distress surveys. This study represents the work being done at Rensselaer Polytechnic Institute in collaboration with the New York State Thruway Authority.

There are no standard procedures for conducting distress surveys at the present time. Available methods vary in cost as well as data quality and range from manual field mapping to visual surveys with automated data logging. These methods involve a significant manual component that results in a number of problems, such as non-repeatability, subjectivity and high personnel costs[6]. Consequently, it has been recognized that automating distress surveys using image analysis is of great significance in objectively evaluating the distresses.

A direct approach to automating distress procedures is via sensed images, either digitized photographs or video images, of pavement surfaces. An advantage of using digitizing cameras to generate a reflected image of the pavement surface is that the observed features can be related to those recognized by the human eye. Mathematical morphology is an image processing technique that was born out of investigation of the relationships between the geometry of the porous media and their permeabilities. Thus, it has its roots in the determination of material properties and defines powerful tools for texture analysis[9]. Pavement structures are considered as composite materials with particles (aggregates) bound together by asphalt or Portland cement concrete mix. Analysis of pavement textures (which result from such a composite structure) could reveal information useful in the assessment of their physical condition, and such analysis provides the rationale for exploring the applicability of the methods available in mathematical morphology.

The present study addresses the development of a computerized system for automating distress data based on mathematical morphology that uses the texture present on the pavement surfaces to analyze cracking as well as other forms of distresses. The goal of the proposed study is to develop and refine morphology-based image analysis algorithms, and evaluate the feasibility of applying this computerized technology to the automation of pavement distress surveys. Findings will be based on the ability of the developed image processing technique to identify distress types and severities on the photographs of asphalt and concrete pavement surfaces.

The remaining text is organized as follows. Section 3 discusses several existing image processing systems for automating distress condition assessment, and also establishes the context of the proposed study. Section 4 presents the proposed research method and discusses the research efforts to date. Section 5 summarizes the relevant task plan.

3. BACKGROUND

The availability of high-speed computers, video and photographic cameras, and image processing software has resulted in the development of a number of early systems for automating pavement distress surveys using computerized image processing.

Automated Road Image Analyzer (ARIA) is a computerized image analysis system developed by MHM Associates Inc.[8], PAVEDIST developed by Acosta et. al.[1] and PAS 1 developed by Pavedex Inc.[5] are examples of computerized image processing systems for automated crack detection. They demonstrated the ability to quantify alligator, longitudinal and transverse cracks. The basic idea involves identifying cracks by their different reflectivity properties. Thus, image regions are separated into different classes where one of the classes corresponds to distresses. Area, transverse and longitudinal lengths, aspect ratio, gray level mean and variance, inertia, etc., are some of the properties used in the classification. Their performance was compared against that of human raters and accuracies up to 90% were reported on certain types of pavements, especially when there is no significant amount of texture.

The several image processing systems that already exist clearly demonstrate the potential for automated processing. However, the majority of them use relatively simple algorithms that can only support crack detection, and thus are not capable of evaluating other types of distresses such as spalling and surface defects. All are subject to difficulties in the presence of texture. In an assessment of the leading technologies in [7], it is reported that it is quite difficult to segregate cracks from texture, particularly for the more open textures of the bituminous pavements. It was also concluded that the existing techniques based on thresholding will generally identify some texture as well as cracks, especially in scenes which have no cracks. Thus, computer identification of pavement distresses from digitized photographs or video images requires the system to perform equally well under a variety of different conditions and requires fairly sophisticated image processing algorithms.

4. RESEARCH METHOD

4.1 Overview

The present study addresses the development of a different approach to automating distress data, one based on mathematical morphology that uses the texture present on the pavement surfaces. A significant feature of the morphological approach is that distresses other than cracking may also be detected and quantified. The proposed normalizing scheme to incorporate a-priori knowledge about non-distressed pavements increases the sensitivity of particle distributions to all types of distresses. This increased sensitivity contrasts with the existing image processing techniques that do not handle such distresses. Another major feature of the proposed study is that it does not involve the development of different algorithms to detect and quantify different distresses. The development of a unified approach to handle different types of distresses under different conditions leads to a significant computational advantage. Finally, the current approach is capable of performing well on a number of different pavement surfaces, including those that exhibit extensive texture[2,4]. Unlike other existing approaches, the current algorithm utilizes texture information and, therefore, is more robust in the presence of pavement texture.

4.2 Mathematical Morphology

Mathematical morphology (MM) is an image processing technique that was born out of investigation of the relationships between the geometry of porous media and its permeability. MM can be used to assess geometric features such as size, orientation, shape, overlap, and distributions of objects in photographic or video images. The power of this technique is based on a structural sorting of texture. Texture is analyzed through the use of geometric probes known as "structuring elements." When different shapes and sizes of these elements are used, different features of interest are highlighted. For example, a circular structuring element of a specific diameter 'd' sorts the texture under study so that the structures possessing a similar geometry (i.e., circles of diameter 'd') are emphasized.

The MM approach is somewhat analogous to sieving a soil sample. Probing (or "opening") an image with an element has the effect of removing from the image all objects smaller than the structuring element. Performing a series of openings with increasingly larger structuring elements of the same shape is similar to shaking a soil sample through a series of sieves with decreasing mesh openings. The generated morphological "opening distribution" is analogous to the amounts of soil retained on screens of various sizes. Thus, the opening distribution provides important information about the size distribution of objects in an image.

4.3 Crack Assessment

The MM approach for crack assessment is illustrated in Figure 1 which shows a thresholded pavement image along with its opening distribution. The opening distribution is obtained by using a horizontally oriented line-shaped structuring element. The length of the line segment is varied from a length of 2 pixels to 46 pixels. From the description of the opening operation, one can qualitatively describe the shape of the distribution in the figure. There is a fine-grain texture in the original image caused by particles having dimensions of about 8 pixels or less. There are also two major cracks running vertically in the image that have much greater widths (approximately 26 to 32 pixels). Consider opening the image with a series of line-shaped structuring elements of successively increasing lengths. The fine-grain texture is continuously removed by opening with lines of length less than 8 pixels. Thus, the opening distribution exhibits a large slope at those scales. Since a line-shaped structuring element fits inside cracks (which are also long features), it preserves cracking until its length becomes longer than that of the crack. Structuring elements of lengths in the range 26 to 32 pixels begin to remove the cracking from the image which results in the sharper slopes at those scales in the distribution.

4.4 Surface Distress Assessment

The qualitative analysis described above shows that an opening distribution generated using a linear structuring element provides information about cracking. Relatively large defects such as potholes can be analyzed similarly. By "normalizing" opening distributions to remove the effect of normal pavement surface texture, distresses such as polishing, raveling, pitting, etc., can also be detected. Without normalization, texture-related distresses can be difficult to identify, because there is often no clear difference between the scale of normal pavement texture and that of the abnormal condition. Normalizing emphasizes all types of deviations from normal surface texture, and therefore can also be expected to increase sensitivity of crack detection (see [2] for details).

The shape of a normalized distribution computed from a pavement image with no distresses is always a straight line parallel to the X-axis at y = 1. Any abnormal texture is revealed as a deviation from the straight line; if there is an excess of particles at any scale, then it is greater than 1, and if there is

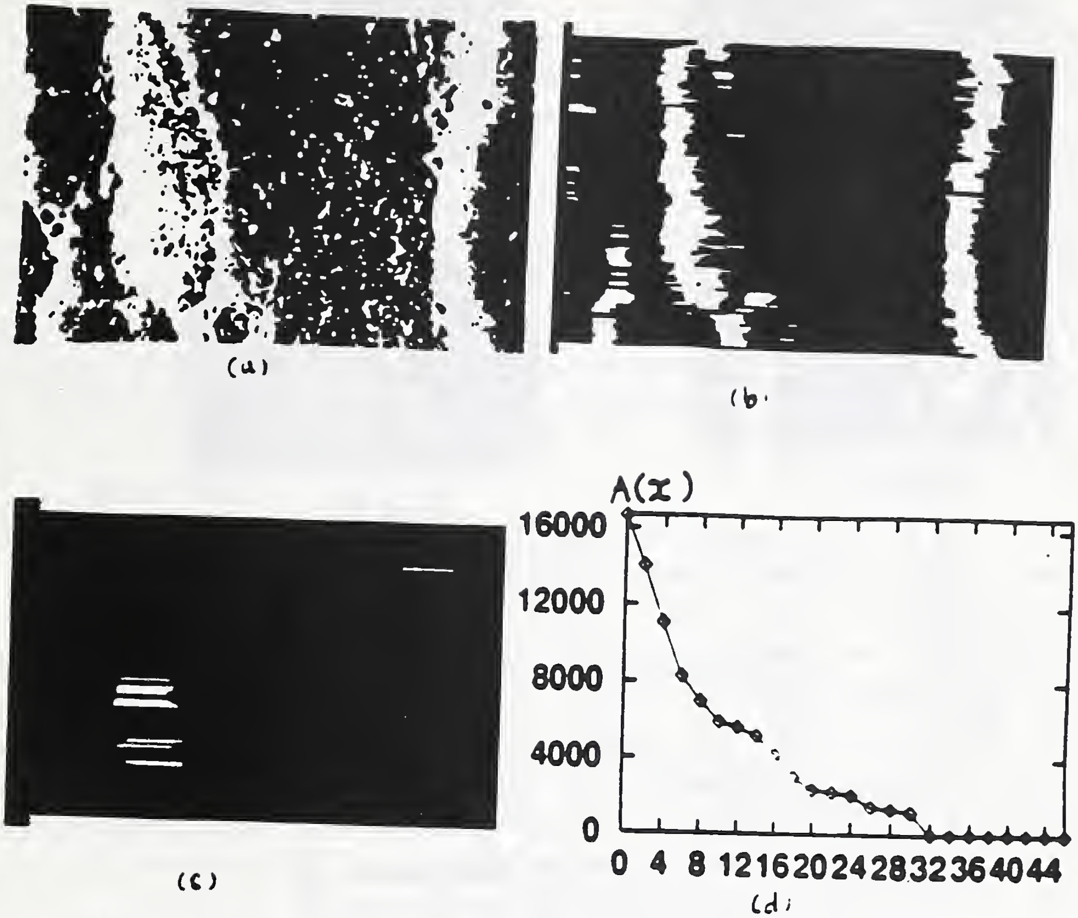

Figure 1: (a) Original image. Results of opening it with a line shaped structuring element of length (b) 8, (c) 30 pixels. (d) Opening Distribution. X-axis: length of the structuring element; Y-axis: area remaining in the image after opening in pixels.

a deficiency at any scale, it is less than 1. In an opening distribution generated from line-shaped structuring elements, cracks, which are large scale features, are revealed as overshoots in the normalized distribution at corresponding scales. Abnormal texture resulting from other types of distresses is revealed as either an undershoot or an overshoot at scales corresponding to the scales of distress. Full mathematical details are presented in [2].

Figure 2 shows the normalized distributions of four images showing shoulder defects. The images are identified by an alphabetic code of the form "ts_d.dd" for brevity. The first character ("t") indicates the type of distress; in this example, all photos are coded "g," and portray shoulder defects. The second

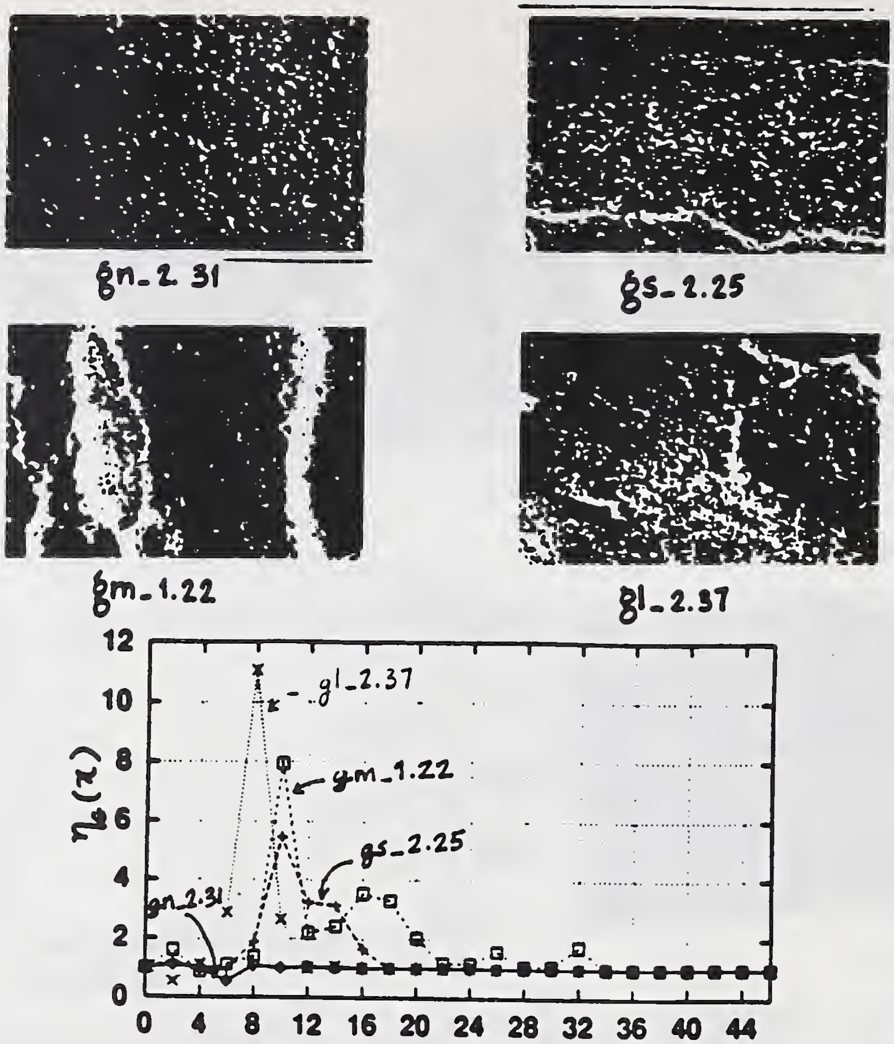

Figure 2: (a) Four pavement shoulder images with defects. (b) Normalized Distributions of the four images. Structuring element is a line. X-axis is the length of the structuring element. Y-axis is the normalized area (dimensionless)

character "s" indicates the distress severity as assessed by trained manual raters. Severity may be none (N), small (S), medium (M), large (L), or total (T), as defined for the New York State Thruway Authority's pavement distress survey [3]. The digits following the underscore are used to identify an image uniquely. Thus, the image "gn_2.31" indicates it is a particular image of a pavement shoulder exhibiting no defects. In Figure 2, the normalized distribution of "gn" image is almost a straight line parallel to the Y-axis at y = 1.0 showing that it has an ideal pavement surface. The rest of the distributions show deviations from the flat line of varying magnitudes at varying scales. The "gs" and "gm" images exhibit cracking and their normalized distributions reveal it as overshoots at large scales (26 and 32 pixels), as expected from the discussion in the previous paragraph. The magnitude of the deviations for the "gm" image is larger than that of the "gs" image indicating the greater severity of its cracking. "gl" image shows a large overshoot at a scales between 4 and 12 pixels. It does not show any deviations at larger scales indicating that it has little or no cracking, and the image "gl_2.37" shows that the distress is present mostly as a surface defect. Thus, normalized distributions detect and quantify cracking as well as other types of distresses[2].

5. TASK PLAN

Different morphological models of ideal pavement textures are being developed to study their use in identifying pavement distresses. The preliminary results show that the morphological approach based on particle size distributions is capable of detecting and quantifying cracking; it also provides information about the overall condition of the pavement, including non-cracking distresses. The results indicate the potential of morphological size distributions for analyzing pavement surface images.

Automating distress condition assessment using computerized image processing is a two-step process. In the first stage, images of the pavement surface are analyzed to derive certain measurements in the image domain. The second stage involves translating these measures into the pavement domain. Most of the research effort to date has been related to the first stage and the normalized distributions represent the resulting image measures. The proposed tasks represent the translation procedure of the second stage.

Specifically, over the one-year period of the study, the feasibility investigation would involve the following tasks:

1) Measure the overall severity of distresses

The overall severity is used to eliminate images that have no significant distress from the analysis. Precise identification of different types of distresses is not required. This information can be obtained by relating the magnitude of the deviations in the normalized morphological distributions with the severity of the distresses.

2) Classification and quantification of cracking

Analysis of the image measures obtained from the morphological distributions to relate them to longitudinal, transverse and alligator cracking. These different classes are based on the direction of cracking. Such information may be obtained by using line-shaped structuring elements oriented in different directions to generate normalized distributions. The normalized distributions may also be analyzed to quantify different types of cracking according to their severity and extent.

3) Assessment of other Surface Defects

Analyze the morphological distributions and relate them to non-cracking distresses like spalling, surface defects, milling etc.

4) Generate a numerical index for the overall condition

Combine the information obtained from the earlier tasks to generate a numeric index that can be related to the overall condition of the pavement. Different weights may be given to different types of defects depending on their importance.

Tasks / Months	1	2	3	4	5	6	7	8	9	10	11	12
Task 1	—	—										
Task 2	—	—	—	—								
Task 3				—	—	—	—	—	—			
Task 4										—	—	—

Table 1: Task Schedule

6. REFERENCES

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[9] J. Serra. Image Analysis and Mathematical Morphology, Academic Press, 1982.

BUDGET

Rough budget for 1 year of support.

Automated pavement distress assessment using morphological image analysis.

Co-PI: Dimitri A. Grivas, Associate Professor, Civil Engineering, RPI
Co-PI: Michael M. Skolnick, Associate Professor, Computer Science, RPI

We estimate that the following level of support will come to a bottom line figure (including fringe and overhead) of about $100,000.

D. Grivas: 10% academic year salary and 1 month summer
M. Skolnick: 20% academic year salary and 1 month summer
One R.A.: Coverage for tuition, salary over academic year and summer.
Other expenses such as computer time, secretarial coverage, supplies and domestic travel.

A Proposal on Automated Crack Detection and Sealing

Avi Kak
Robert Cromwell
Robot Vision Lab
Purdue University

Introduction

We believe that the time has come for a concerted effort at applying the science and technology of automation to the automation of road surface inspection and repair. This proposal has two objectives: 1) To develop the technology of automated inspection of road surfaces; and 2) To develop a prototype of a mobile robotic system that can be hitched to a maintenance vehicle traveling at approximately 10 miles/hour for automated sealing of the cracks found. The data produced through inspection would be analyzed automatically for flagging the sections of highway in need of repair. In addition, each damaged section of the highway would be graded according to the severity of the cracks and other manifestations of deterioration. Furthermore, the cracks whose severity exceeds a certain treshold will be sealed automatically by the robotic system. The design of the automatic sealing arm will make use of the neural-network and fuzzy-logic based kinematic control strategies we have developed recently [PacMin93a, PacMin93b].

Why Purdue Robot Vision Lab

During the last decade, the Robot Vision Lab (RVL) at Purdue has produced some of the most computationally efficient and robust algorithms for sensor-based robotics. (These accomplishments have formed the basis of an ongoing active collaboration with industry in the area of advanced automation.) To state two of our most significant accomplishments during the last few years: RVL has developed the fastest 3D vision system for bin-picking [CheKak89, KimKak91]. On run-of-the-mill laboratory computing hardware, this system can recognize objects, including those that are non-polyhedral and non-convex, and compute their poses in just a few seconds. And, RVL has developed the fastest vision-based mobile robot navigation system that allows a robot to navigate indoors at speeds of 9 to 12 meters per minute using computing hardware of no more than 16 MIPS power [KosKak92]. These developments have been made through the discovery of new data structures, for representing objects and space, and of new control strategies for robust decision-making. More recently the laboratory has also developed neural-network and fuzzy-logic based nonlinear control strategies for kinematic and dynamic control [PacKak93a, PacKak93b].

Is Robotic Crack Sealing Feasible?

Robotic sealing of longitudinal cracks while the maintenance vehicle is in continuous motion at 10 mph has already been demonstrated by the California Department of

Transportation. This was done by attaching a conventional robotic arm to the rear of the vehicle and using a vision system to guide the placement of a sealer nozzle on the crack. While evidently a wonderful demonstration in the use of robotics and vision to highway maintenance, the use of a conventional robotic arm, designed originally for pick-and-place operations in a factory, meant that this effort was preordained to not succeed for the sealing of transverse cracks with the vehicle in motion.

Evidently, an entirely new kind of a robotic arm is needed for the task. In Fig. A, we have shown a concept drawing of such an arm, although variations on the depicted theme are certainly possible. Basically, the arm will have flixibility to scan along a transverse crack while the vehicle is in motion longitudinally. Assume that initially we want to design a system that would allow the vehicle to move down the road at 10 mph. This speed translates into 176 inches per second. Now let's assume a lane width of 12 feet. The California work has already demonstrated that the viscosity of the sealing compound is such that the nozzle can move at approximately 10 mph, meaning at 176 inches per second, while ejecting the sealing compound. Therefore, speaking conservatively, it will take up to one second to fill up a transverse crack.[1] During this interval, the vehicle will experience a forward translation of 176 inches. The question then becomes whether it would be possible for a robotic arm to extend itself by about 15 feet. We believe that a scissor-shaped kinematic chain depicted in the figure would be able to do so. Such a chain would be mounted on a 20 foot boom that would be anchored at its free end on top of wheeled support. **Note that for actuation along the boom, only the last link of the scissor chain will be coupled with the threads on the boom; the other links will simply ride over the threads. Also note that the entire boom will be pivoted by a motor installed over the free end; the rotation will be caused by the turning the wheel under the free end of the boom.**

An obvious shortcoming of the mechanism shown in the figure is that once a transervse crack is filled up, the arm will not be able to fill up any further transverse cracks until the it is retracted. Assuming it takes another second to retract the arm, that would imply that the vehicle would not be able to fill up the transverse cracks that are spaced more closely than 30 feet. While the technology is still in the development phase, a possible way to circumvent this difficulty would be to make multiple passes on a highway. So, if the cracks are relatively infrequent, with fault-free spaces of length greater than 30 feet between the consecutive cracks, a single pass would suffice. However, if the frequency of transverse cracks is, say, N cracks every 30 feet, it would take N passes over the highway to seal them up.

Possible Payoffs from the Proposed Research

In the following we describe a proposed roadway inspection system. If the objectives could be accomplished, the following benefits would be realized:

- ☐ Roadway defects such as cracks would be detected by our system, with performance better than that of human inspectors. The minimum crack size would be less, meaning that preventive maintenance could be carried out earlier,

[1] Of course, the precise time required to fill up a crack will also depend on the width and the depth of the crack; both of these parameters can be estimated with a range sensor. We will assume that it is possible to regulate the flow of the sealant to adapt to the width and the depth of the crack.

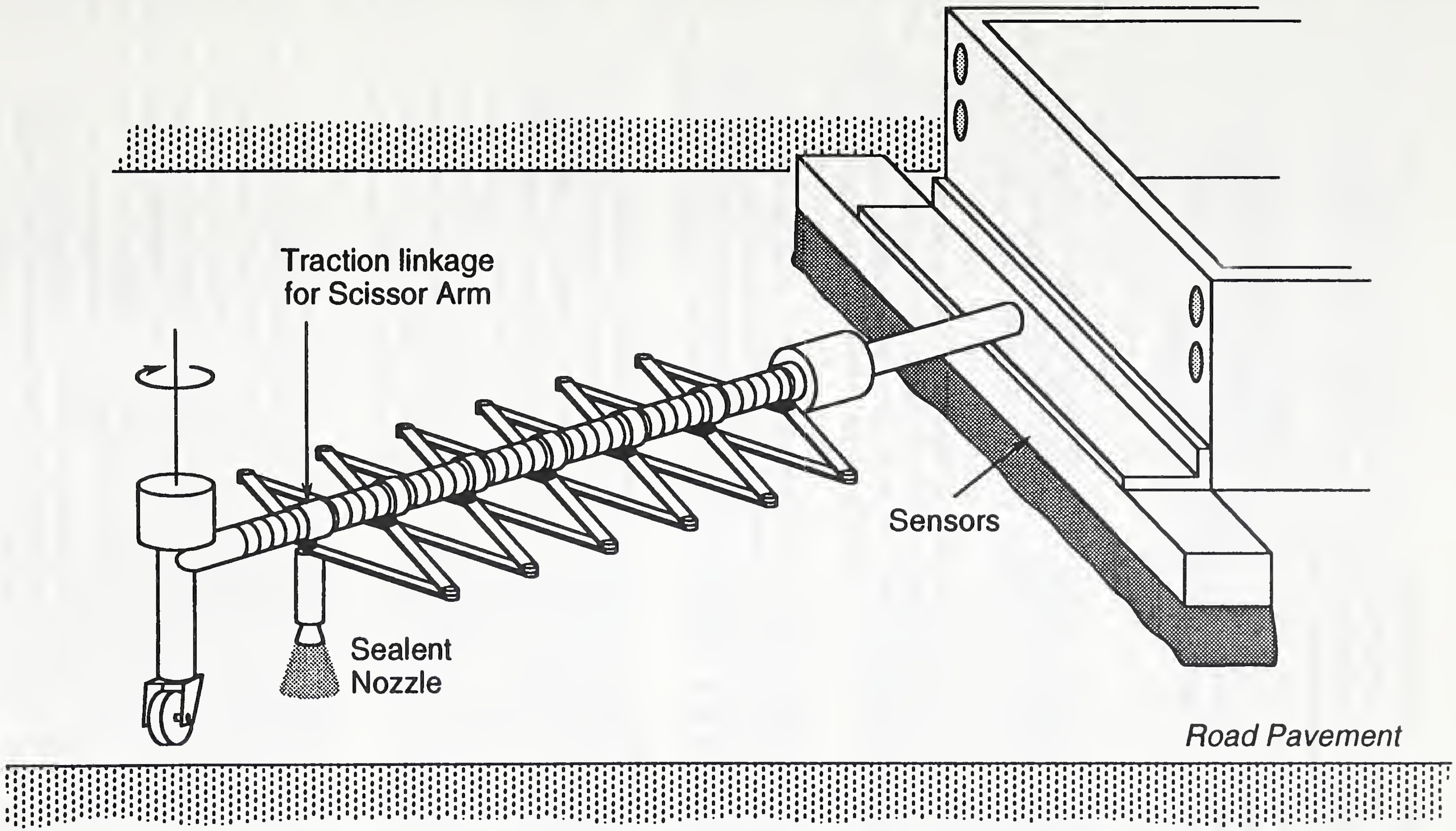

FIG. A: Concept drawing of a planar robotic arm for sealing longitudinal and transverse pavement cracks. See text for details.

leading to increased savings in repairs.

- Quantitative measures of performance – detection rate, false-alarm rate, etc. – could be accurately characterized. This is not currently possible with the highly subjective human decision-making process.
- As the inspection (and, for defects of limited severity, the repair) could be done at highway speeds, much more roadway than the currently limited sample could be inspected. What is more, the repair would be carried out simultaneously. Inspection and repair would become a one-pass operation.

Discussion

Road surface inspection is a boring, repetitive task consisting of inspection and quantitative evaluation of a manufactured surface. As such, it is an ideal application of machine vision. In the following we propose methods for the automatic detection of roadway defects, and, where possible, their automatic repair.

Human experts recognize many distinct forms of road surface damage or deterioration; [GADOT] presents one of many classification schemes. However, all forms are presently detected by human inspectors who simply look at the road. This means that photometric and range measurements would possess adequate information for the detection of all currently recognized problems.

Figure 1 shows a cross-section of a road with some commonly recognized problems labeled. Since a pothole is the largest such structure, it is easy to detect. the aberrant profile exhibited in the range data clearly indicates its presence and accurately defines its boundaries. The exposed aggregate would be of a different color, and so a pothole would also be easily detected in photometric imagery.

We have turned our attention to a more difficult inspection problem, crack detection and repair. While cracks can grow quite wide, thus becoming easy to detect, it is best if they are detected early so that prompt repair can prevent further damage. This requires the detection of quite small cracks, which means that vision data must be gathered at a fine scale, so that features only 0.1" wide or even narrower be detected. Since cracks may be transverse or longitudinal, or at any angle in between, it is necessary to gather data at similar sampling rates both across the road and along the direction of travel. The requirements for storing the amount of data associated with even a short segment of a road would be astronomical. The only solution is a system that analyzes the road as it travels over it, storing only the information needed to describe detected problems.

What sort of information would be useful for making this type of decision? We feel that both range and reflectance information should be used. Consider the highly schematic system shown in Figure 2. Imagine an array of balls, or wheels, of differing diameters, free to roll along the road and follow its contour. If there were a way to record the up-and-down motions of these individual sensors, the result would be a 3-D map of the road surface showing its texture and shape at varying scales. The larger balls or wheels would describe the overall shape of the road, and would be useful for the detection of such relatively large-scale phenomena as rutting. The smaller sensors would measure the surface at a finer scale, detecting narrow cracks.

We took a sample of slightly deteriorated road surface, and used a robotic manipulator with a force-torque sensor to drag a probe over the sample surface, attempting to maintain constant force/torque conditions. Records the paths of the robot arm as it moved the probe in a grid pattern over the sample yielded measurements of a form similar to those of our hypothetical system of Figure 2. Some of this data is plotted in Figures 3 and 4.

The problem is that electro-mechanical recording devices are too slow to gather data of the desired scale while the platform moves at a realistic speed. For this reason we suggest using range sensors of the general types commonly used in machine vision. Figure 5 shows a structured-light range sensor – a system in which a projector casts a distinctive pattern on a scene and a camera views the scene from an offset position. Knowledge of the optics and geometry of the system allow the *(row,column)* information gathered by the camera to be converted into *(x,y,z)* measurements, building a range map of the road as the system travels over it. The range resolution characteristics are a function of the sensor design, it would need to be designed so that the structures of interest can be seen.

How, then, would the analysis be done? We suggest the application of morphological operators to the range map, among other techniques. Figure 6 shows the z component of the (x,y,z) measurements for a sample of deteriorating asphalt, with greater values of z represented by brighter pixels. The crack network leading from the left to the bottom, via the center, is very noticeable. Figure 7 shows a similar image for two samples of concrete, one of which is cracked. Again, the flaw is strikingly obvious. Morphological operators, which can be mathematical models of rolling balls, make such features more striking. Figure 8 shows the application of such an operator to the image of z as intensity for the concrete samples. Other than the ends of the samples, the only noticeable feature is the crack.

For details that could be seen in simple photometric imagery, a system similar to that of Figure 9 would suffice. A camera with multiple light sources would view the road as the system was transported. Again, no attempt should be made to store the imagery. It should instead be interpreted as it is gathered, and only symbolic information about defects and their locations retained.

Figure 10 shows what is called registered intensity data for the asphalt sample – it is the intensity measurements made at the same locations for which (x,y,z) values were measured, with z displayed in Figure 6. Similarly, Figure 11 shows registered intensity data for the concrete samples. Morphological operators can also be applied to the photometric data, as shown in Figure 12.

Our proposed system would thus make a large number of measurements of each visible segment of the road surface. What should be done with these multiple channels of information? We feel that an architecture similar to that shown in Figure 13 might produce optimal results. Morphological operators of differing characteristics would be applied to both range and photometric imagery, and the outputs applied as the input to neural networks.

Once the cracks had been detected in imagery, the information about the precise location of the sensor platform at the time the data was gathered would be used to drive machinery appropriate for sealing that type of surface. Our experience with mobile robotics indicates that it would be a mistake to rely on odometry to coordinate actions across several vehicles. If the sealing is done by a second vehicle, then some sort of accurate relative positioning method is needed to accurately drive a "blind" repair arm. We feel that the best solution would be to have the repair done from the same platform, so a rigid frame of reference between sensor and actuator is maintained. Some form of visual servoing might be needed to drive the end effector along the crack. That task is similar to the seam-tracking done by existing welding robots, and so a mature technology is available for application. Given that the robotic manipulators will be mounted on a moving platform, some work is obviously needed in the area of dynamic path-planning and in the coordination of the positioning of the end effector with respect to the motion of the vehicle.

Performance

An important question relevant to this proposal is: How fast can such inspection and repair be carried out simultaneously? In other words, what will be the speed of the vehicle on which this inspection and repair system will be mounted? If inspection alone were our objective, we believe that could be done at highway speeds using a bank of laser beams, each scanning a small area of the road surface; in other words, the entire inspection process could be carried out in a highly parallel fashion using a bank of rather inexpensive microprocessors, each microprocessor processing the output of a single laser beam and making local decisions concerning the state of the road surface. However, with the added objective of real-time repair, the overall speed will be limited by the kinematics and dynamics of the robot arm sealing the cracks. While it would be relatively easy to fill the longitudinal cracks, for filling the transverse cracks the driver of the maintenance vehicle will have to relinquish the speed control to the robot arm. In other words, the sensors mounted on the robot arm will decide how fast the arm will be able to move to fill a transverse crack and will automatically adjust the speed of the vehicle accordingly. From our preliminary calculations at this time, we believe that it would be possible to design a prototype planar arm, with two degrees of freedom, that would allow a vehicle to move at approximately 10 miles per hour while crack filling operation is going on.

Deliverables

This research effort will progress along two parallel tracks during the first two years and then, in the third year, the two tracks will be merged. One track will deal with the development of 2D and 3D vision algorithms for robust detection, delineation, and characterization of cracks. The second track will focus on the development of the special arm needed for the task. Initially, the arm will be attached to a translational motor in the laboratory to simulate vechile motion. This setup will be used fine tune the ability of the arm to track what will be cracks simulated with the help of synthesized patterns on the lab floor. In the last year, the vision algorithms will be installed in the controller of the arm and entire system field tested. The main deliverable of this research effort will be the new robotic arm, the controller for the arm, and the sensory system.

Budget Justification

Support is being requested for 10% of time for the PI, 25% in summer, and three graduate research assistants. For the engineering effort needed to fabricate the arm and the controller for the arm, the budget includes a full-time engineer, a full-time technician/mchinist, and a full-time software/control engineer. While two of the graduate assitants will spend their time on the software aspects of the program, one will focus on the research aspects of the hardware issues. We believe that the parts for the planar robotic arm and the associated controller will cost roughly $40,000. The cost of the sensory system and a processor for the 2D and 3D information would cost $38,500. for building a shrouded structured-light sensing system that would work in an outdoor environment. This system will include a high-speed image processing system for grabbing multiple video frames and for video-rate low-level processing of these frames (cost: $33,000), two high-quality CCD color cameras (cost $3,000), multiple laser sources (cost:

$2,000), various and sundry components for mounting the lasers and cameras (cost $500).

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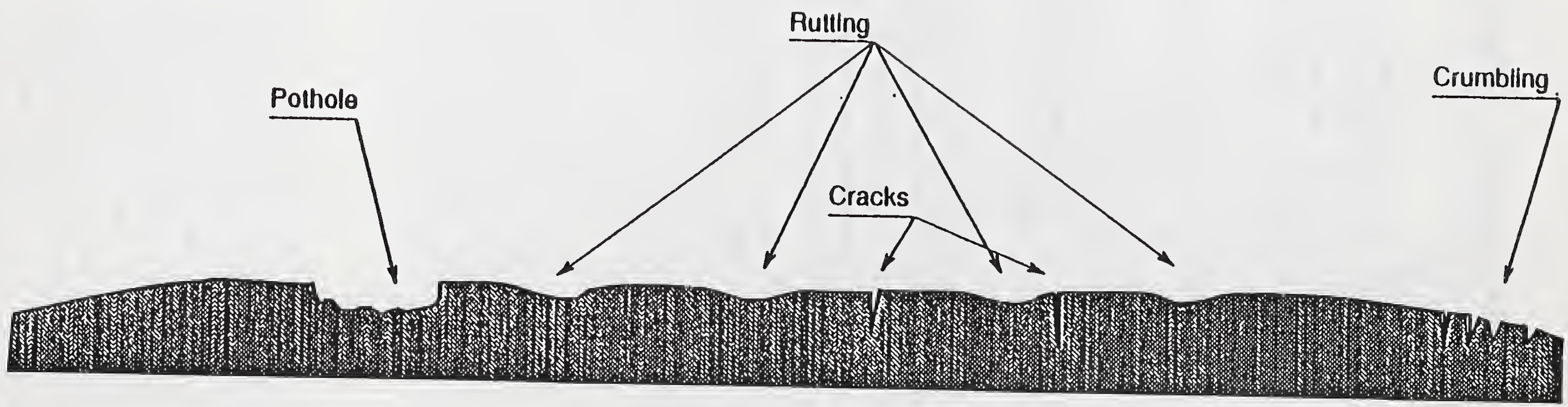


Figure 1

Robot Vision Lab, Purdue University

Rolling-Ball Contact Data Gathering

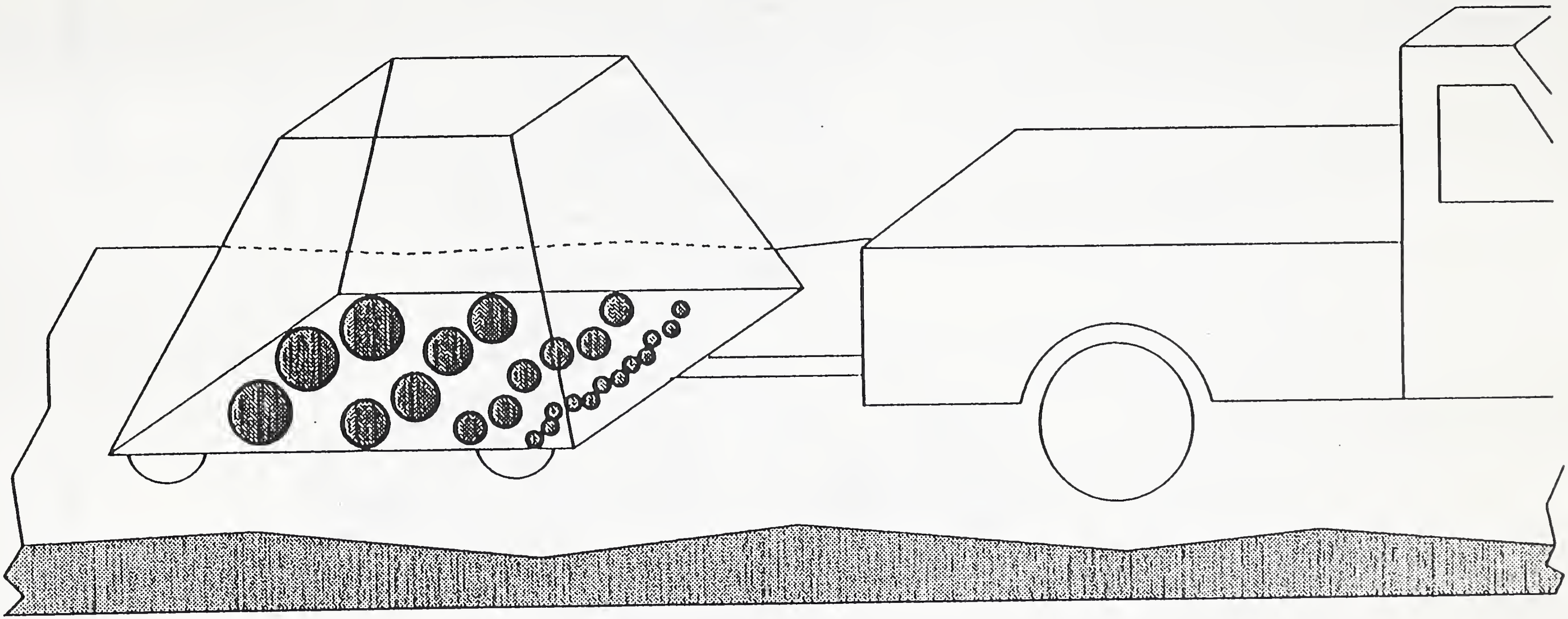
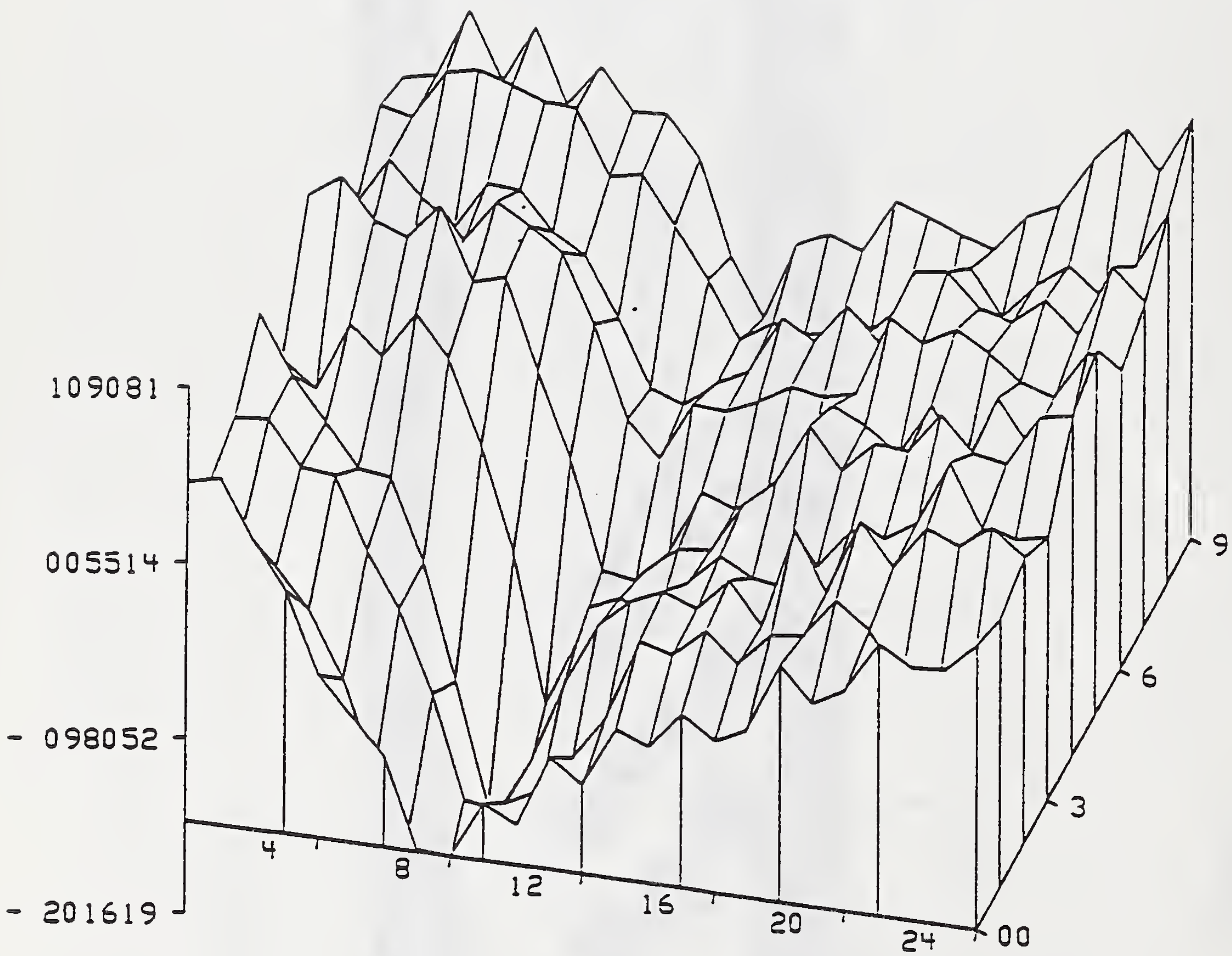


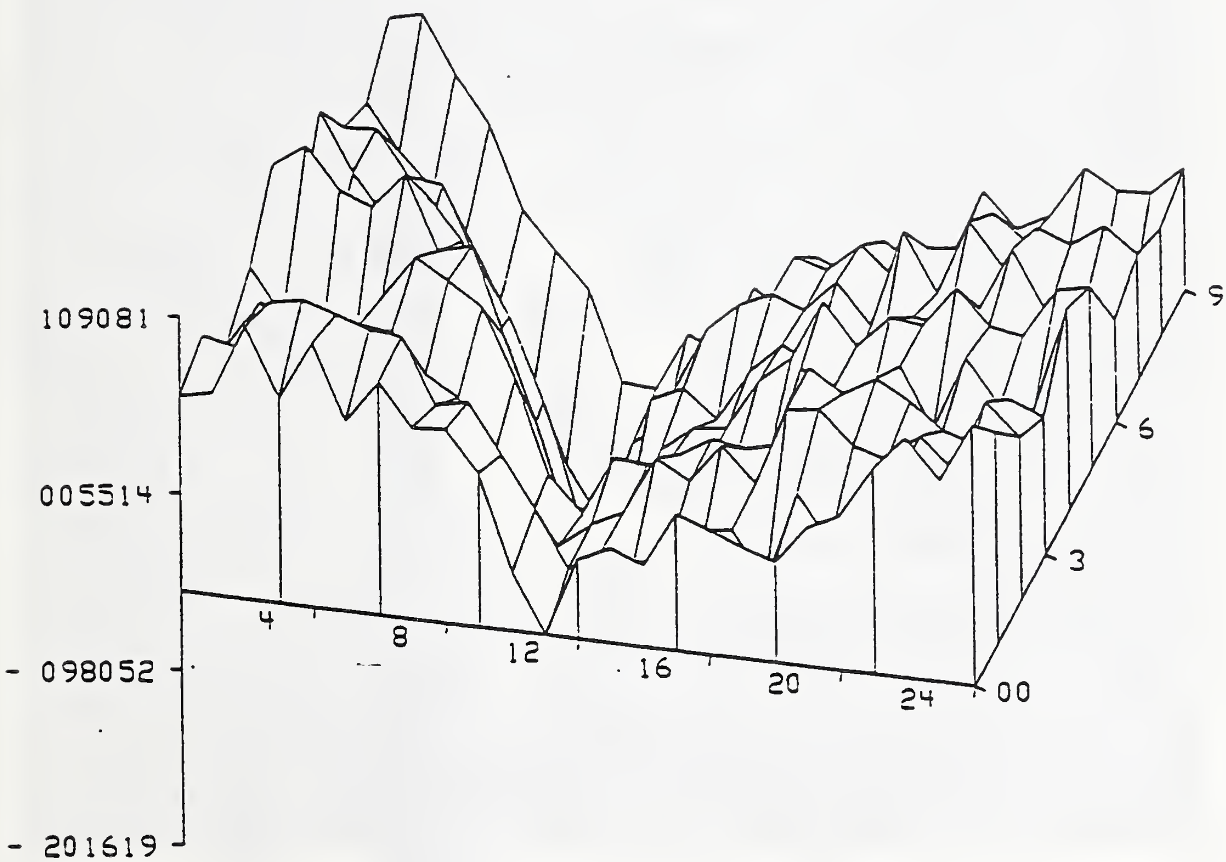
Figure 2

Robot Vision Lab, Purdue University



ɟure 3

Robot Vision Lab, Purdue University



ɟure 4

Robot Vision Lab. Purdue University

X-scan Range Data Gathering

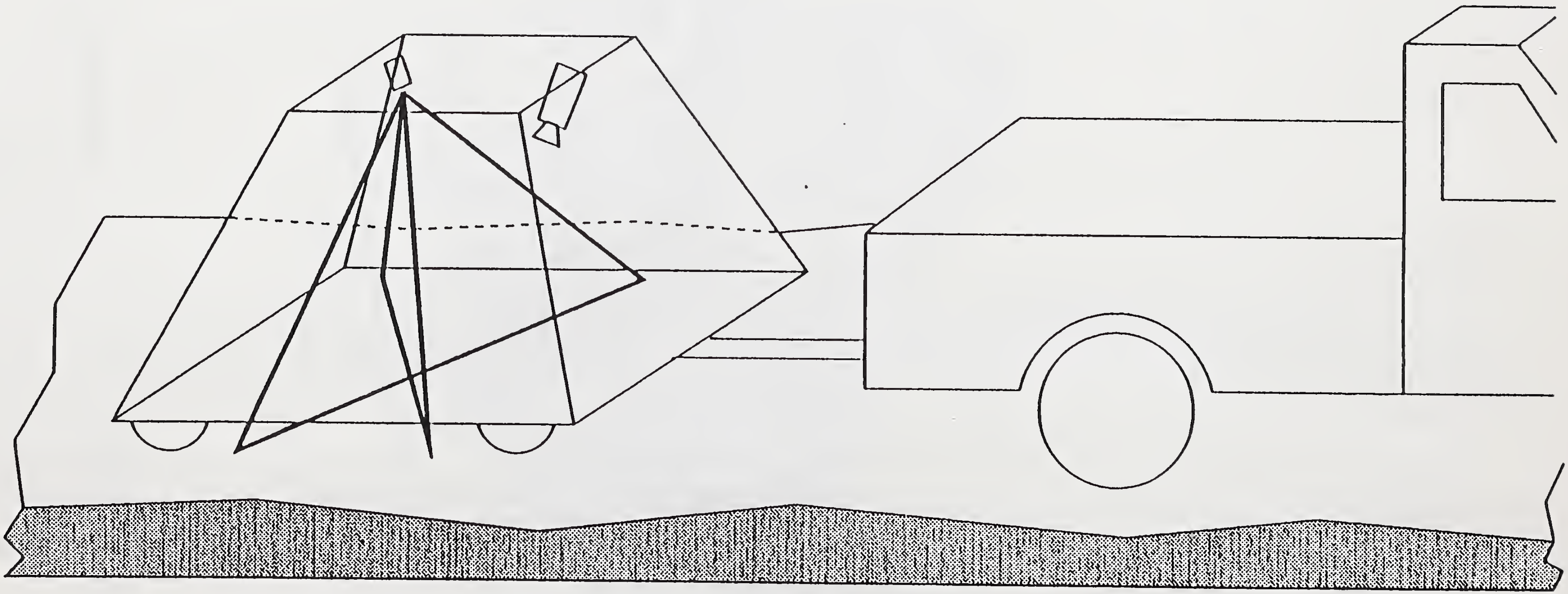
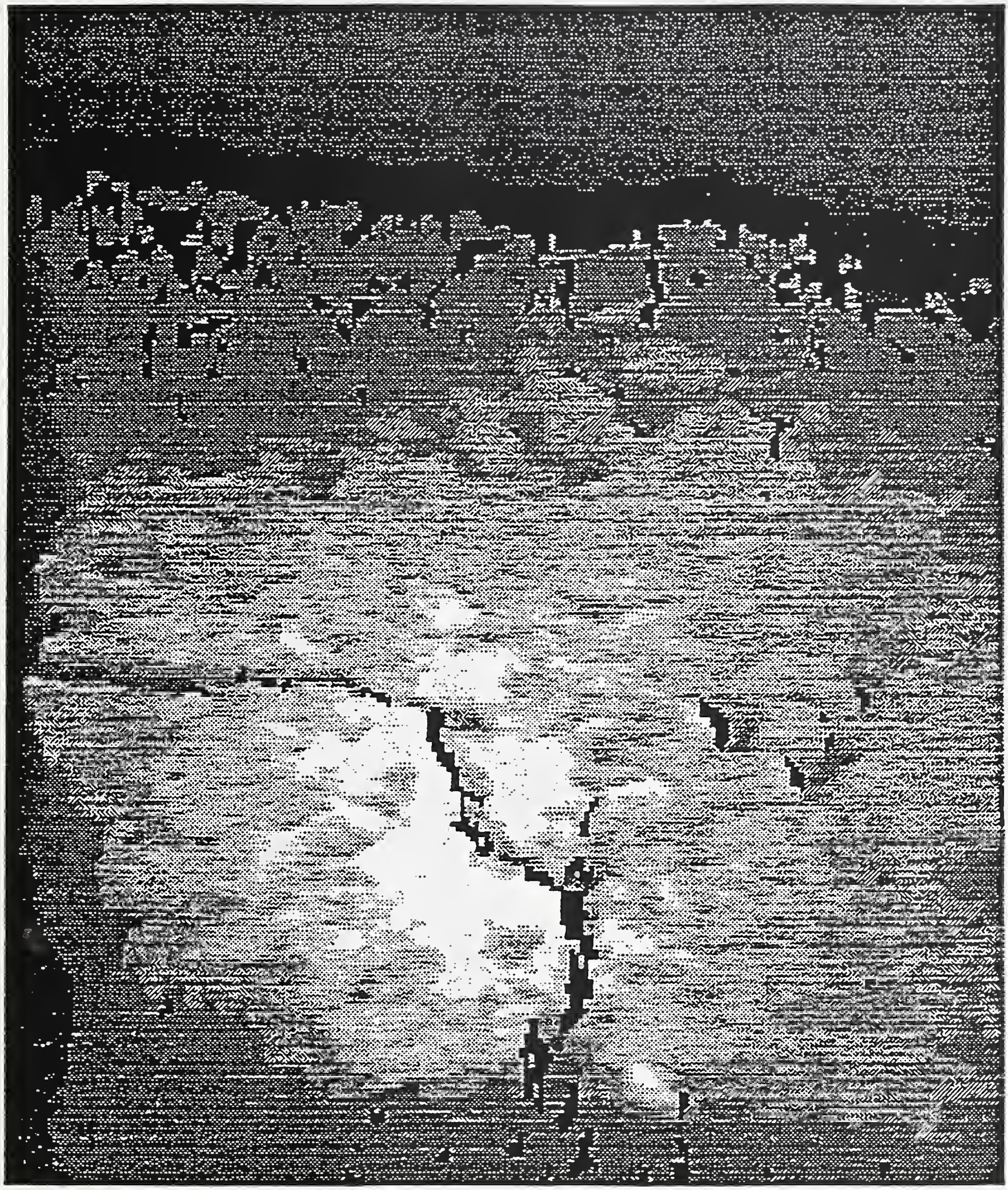


Figure 5

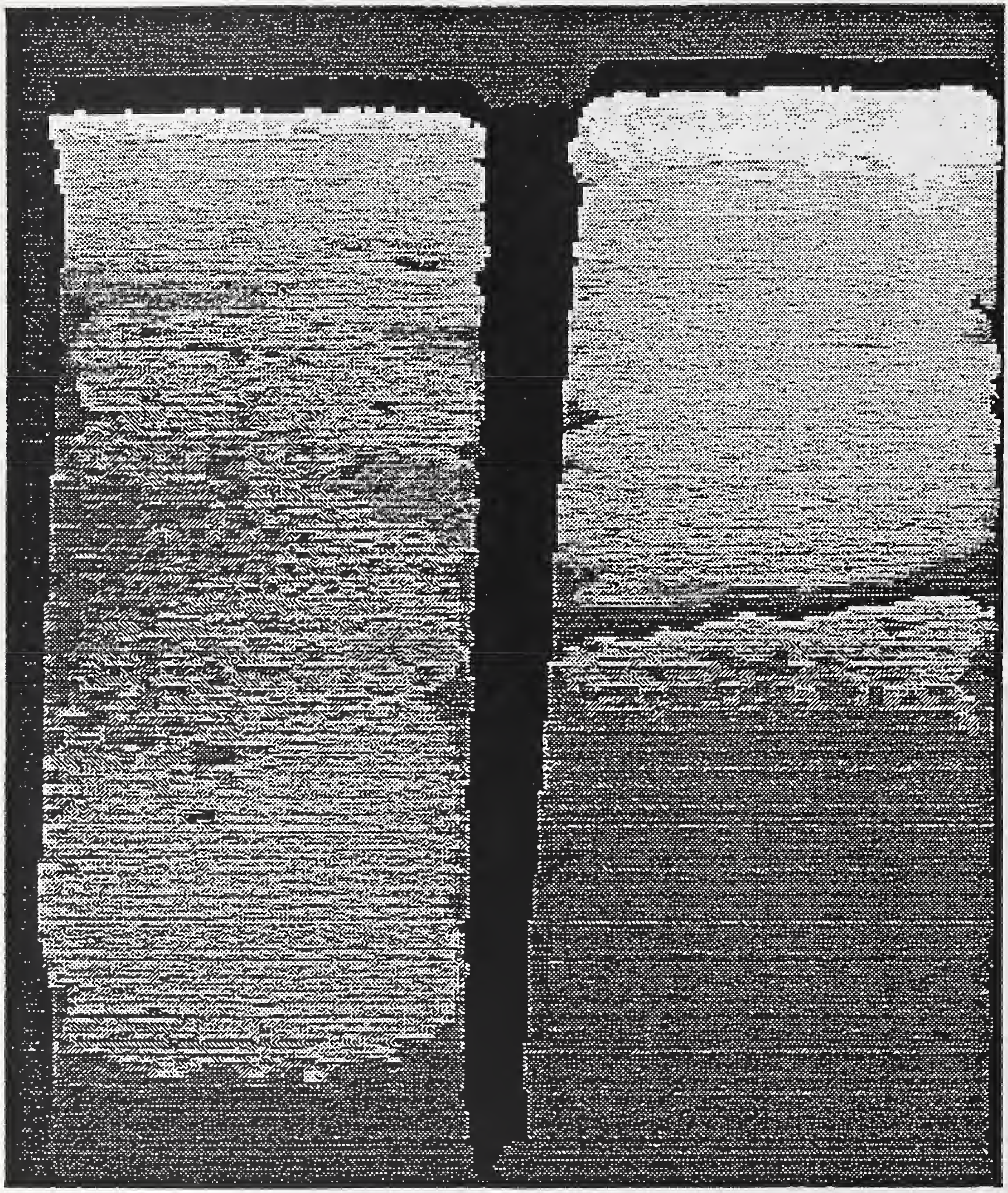
Robot Vision Lab, Purdue University

Z as intensity



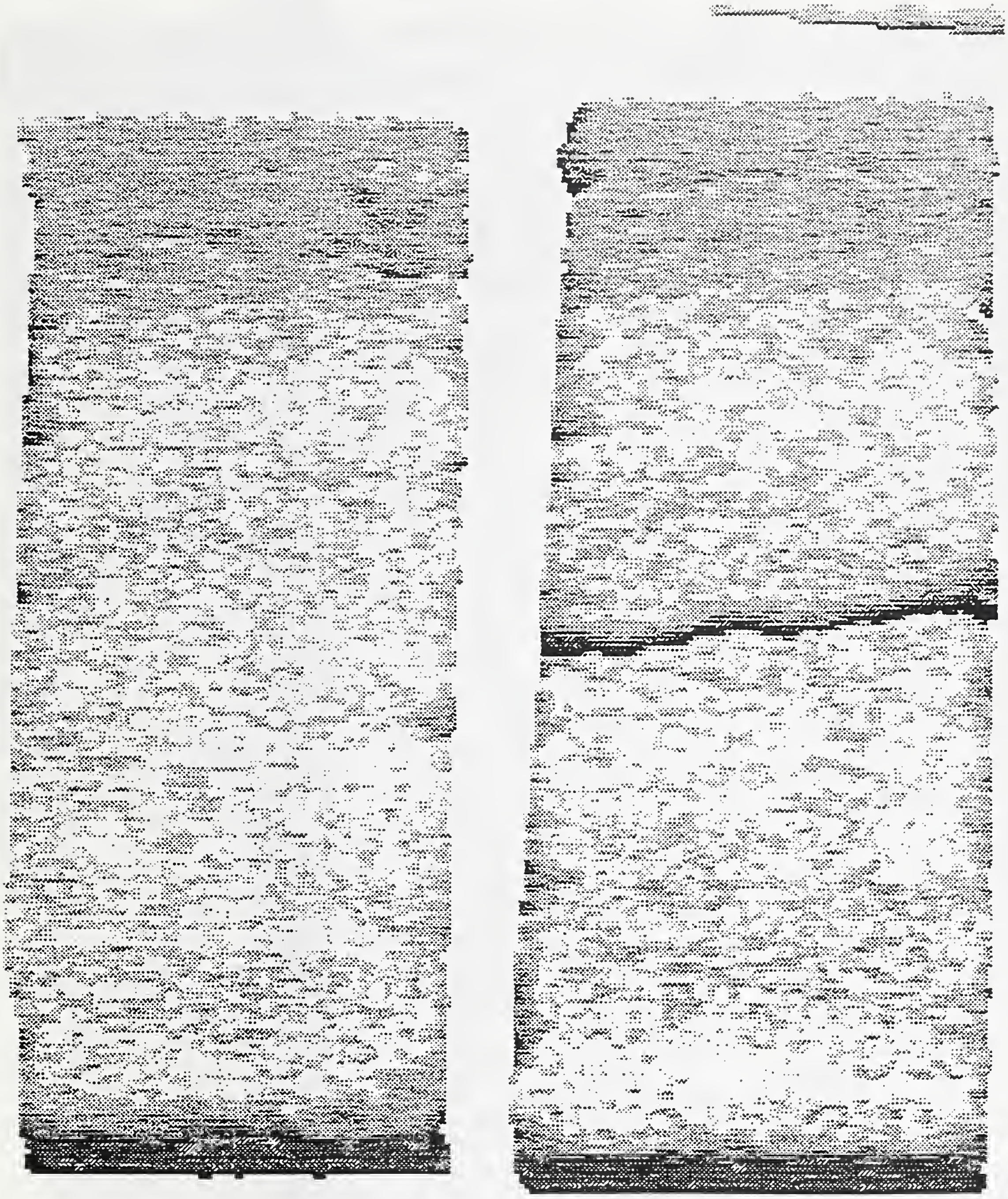
ure 6

Z as intensity



re 7

rolling_ball(Z)



re 8

Photometric Data Gathering

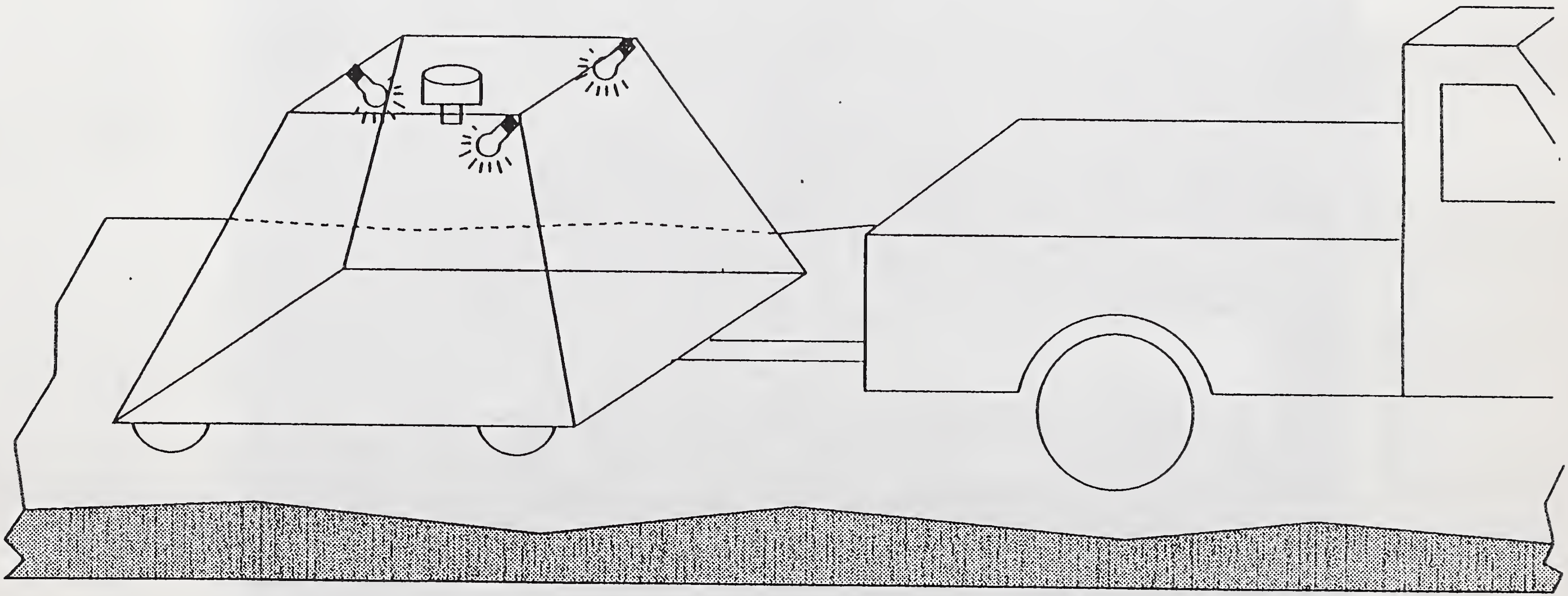
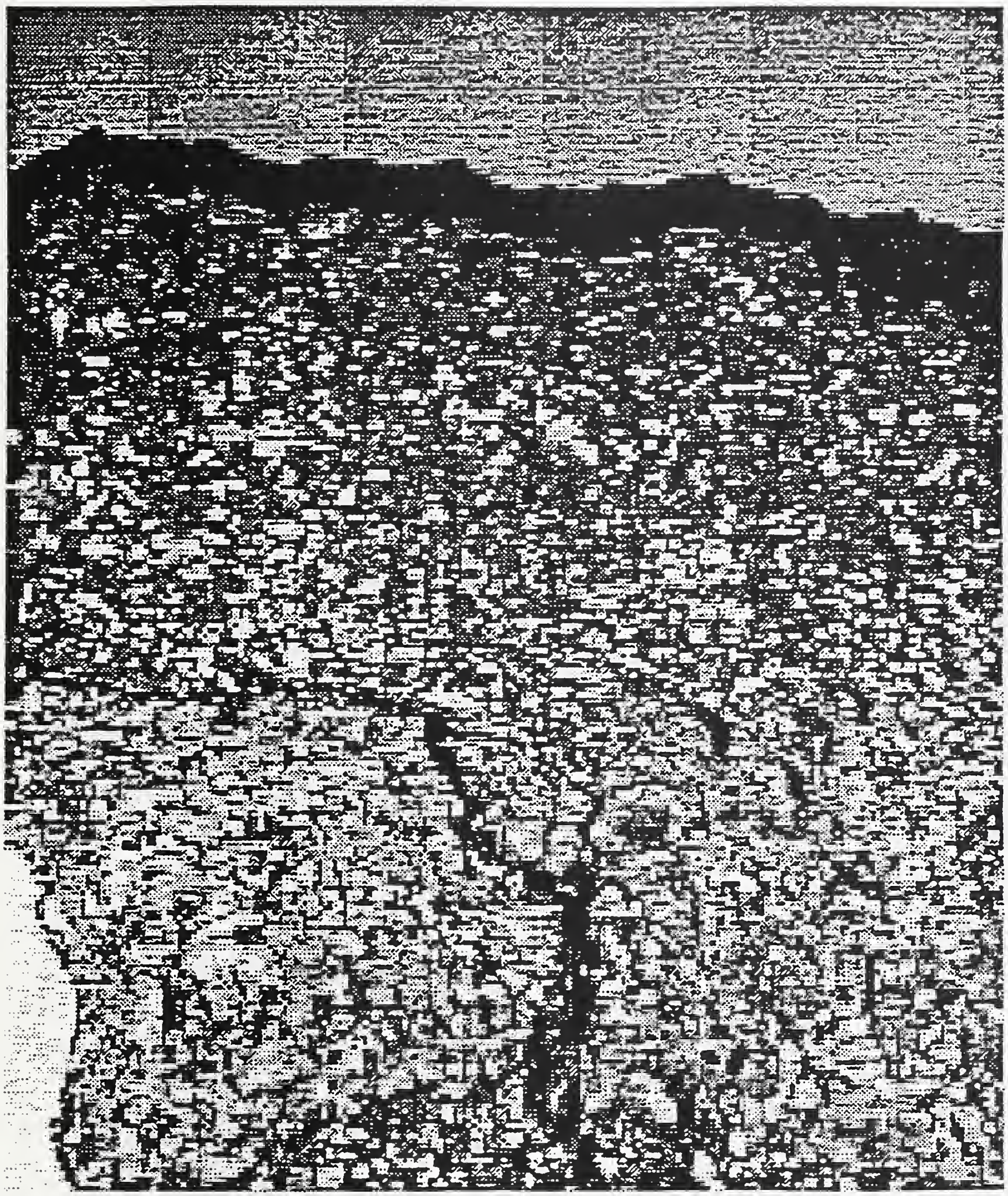


Figure 9

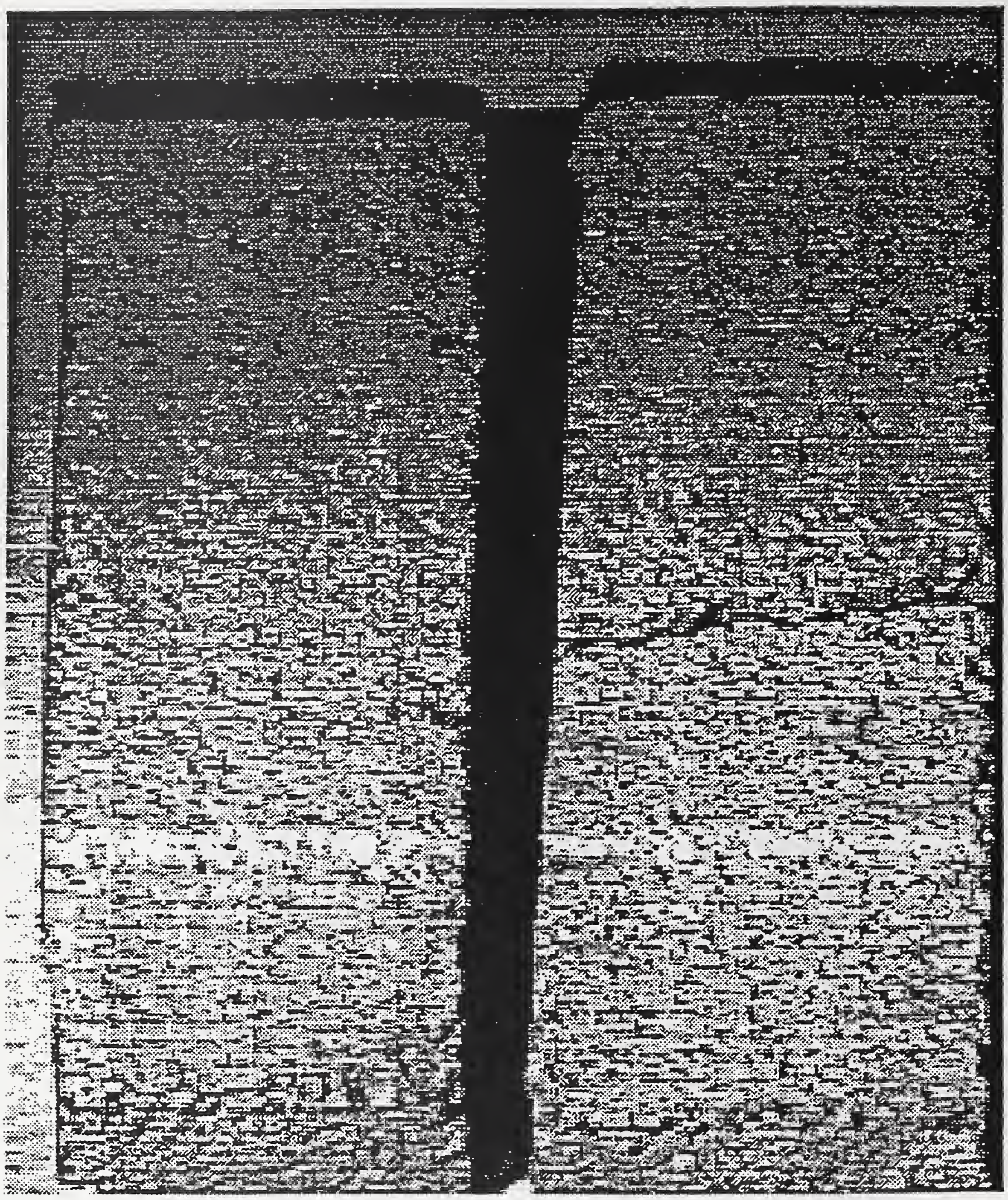
Robot Vision Lab, Purdue University

Intensity image



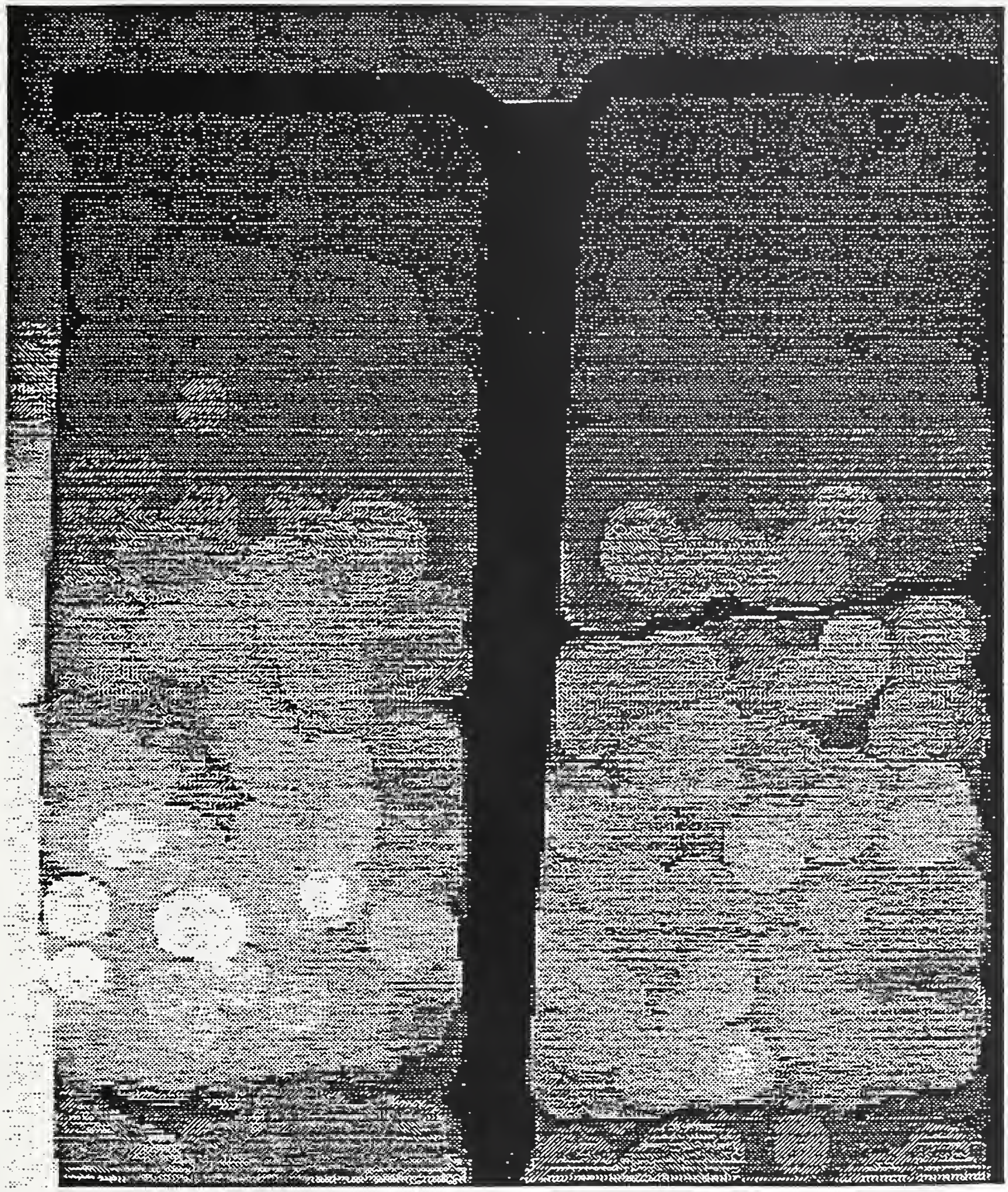
ɪure 10

Intensity Image



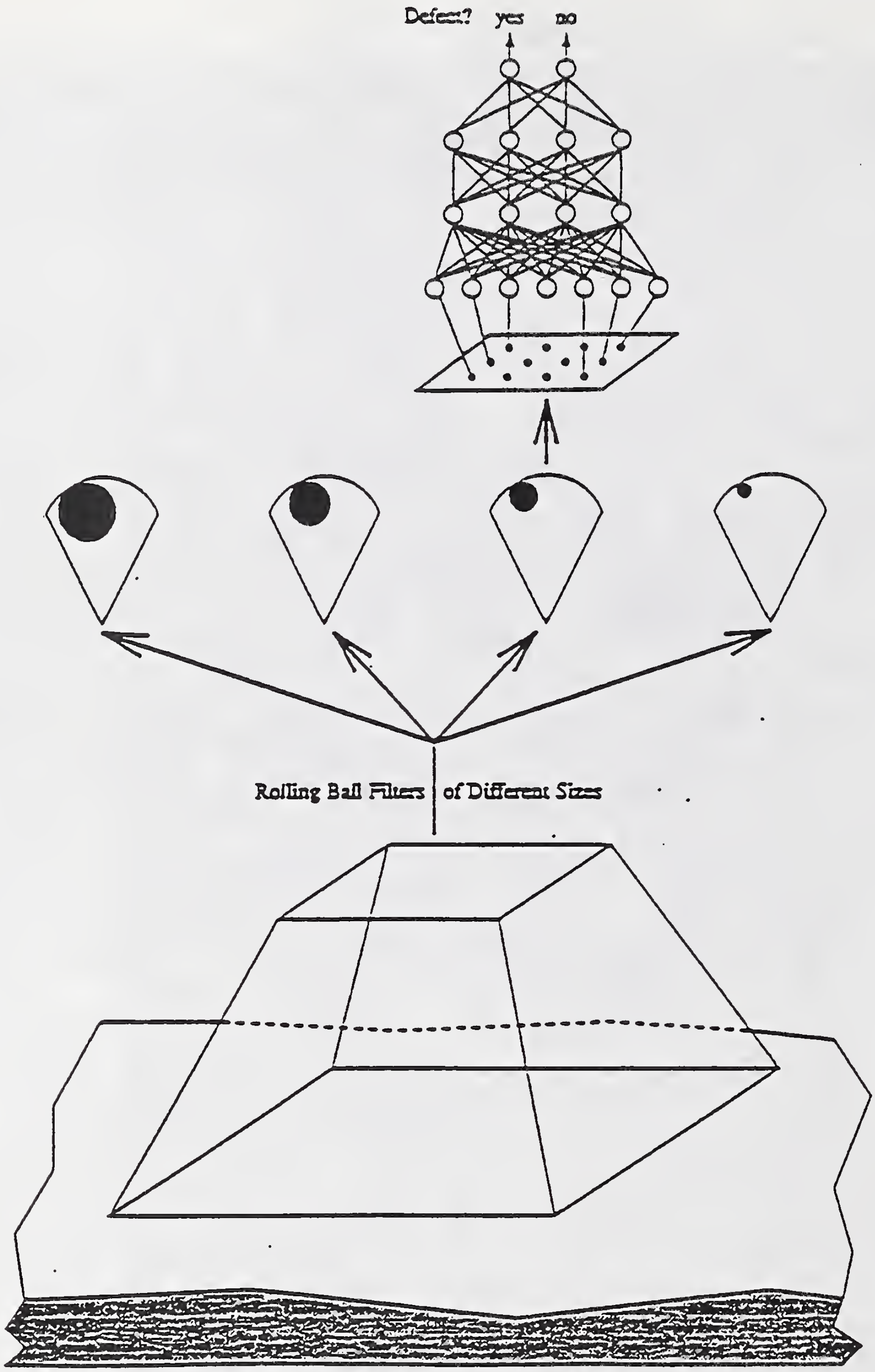
ɜure 11

rolling_ball(intensity)



gure 12

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



ȷure 13

PURDUE INTERNAL PURPOSES ONLY

For the period 01/01/1994 through 12/31/1994

A.	Salaries and Wages		
	1. Senior personnel		
	Faculty associate		
	A. Kak	0.10 AY	13212
		0.25 SS	9528

	Subtotal		22740
	2. Other personnel		
	Professional		
	Software Engr	1.00 FY	41000
	Professional		
	Hardware Engr	1.00 FY	41000
	Professional		
	Technician	1.00 FY	38745
	Graduate assistant		
	Grads.	2.00 AY	47150
		1.75 SS	8050

	Total salaries & wages		198685
	Grad fee remission		6012

	Total compensation		204697
B.	Fringe Benefits		

	Total fringe benefits		23240

C.	Total compensation and fringes		227937
D.	Non-personnel direct costs		
	7-8430 Travel - Domestic		3000
	7-8499 Other S & E		2826
	7-8998 Scientific Equip-New Robotic Arm		40000
	7-8998 Scientific Equip-Sensory System		38500

	Total non-personnel direct costs		84326
E.	Total direct cost		312263
F.	Indirect cost 0.510 of MTD cost		116153

G.	Total cost	$	428416
			=======

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PURDUE INTERNAL PURPOSES ONLY

For the period 01/01/1995 through 12/31/1995

A.	Salaries and Wages		
	1. Senior personnel		
	Faculty associate		
	A. Kak	0.10 AY	14269
		0.25 SS	10290

	Subtotal		24559
	2. Other personnel		
	Professional		
	Software Engr	1.00 FY	43050
	Professional		
	Hardware Engr	1.00 FY	43050
	Professional		
	Technician	1.00 FY	40682
	Graduate assistant		
	Grads.	1.75 AY	43050
		1.75 SS	8400

	Total salaries & wages		202791
	Grad fee remission		6582

	Total compensation		209373
B.	Fringe Benefits		

	Total fringe benefits		24480

C.	Total compensation and fringes		233853
D.	Non-personnel direct costs		
	7-8430 Travel - Domestic		2367
	7-8499 Other S & E		2368
	7-8998 Scientific Equip-New Robotic Arm		40000
	7-8998 Scientific Equip-Sensory System		38500

	Total non-personnel direct costs		83235
E.	Total direct cost		317088
F.	Indirect cost 0.510 of MTD cost		118323

G.	Total cost	$	435411
			=======

PURDUE INTERNAL PURPOSES ONLY

For the period 01/01/1996 through 12/31/1996

A.	Salaries and Wages		
	1. Senior personnel		
	Faculty associate		
	A. Kak	0.10 AY	15411
		0.25 SS	11113

	Subtotal		26524
	2. Other personnel		
	Professional		
	Software Engr	1.00 FY	45202
	Professional		
	Hardware Engr	1.00 FY	45202
	Professional		
	Technician	1.00 FY	42716
	Graduate assistant		
	Grads.	1.50 AY	38899
		1.50 SS	7590

	Total salaries & wages		206133
	Grad fee remission		7206

	Total compensation		213339
B.	Fringe Benefits		

	Total fringe benefits		25781

C.	Total compensation and fringes		239120
D.	Non-personnel direct costs		
	7-8430 Travel - Domestic		1830
	7-8499 Other S & E		1829
	7-8998 Scientific Equip-New Robotic Arm		40000
	7-8998 Scientific Equip-Sensory System		38500

	Total non-personnel direct costs		82159
E.	Total direct cost		321279
F.	Indirect cost 0.520 of MTD cost		122498

G.	Total cost	$	443777
			=======

PURDUE INTERNAL PURPOSES ONLY

For the period 01/01/1994 through 12/31/1996

A.	Salaries and Wages		
	1. Senior personnel		
	Faculty associate		
	A. Kak	AY	42892
		SS	30931

	Subtotal		73823
	2. Other personnel		
	Professional		
	Software Engr	FY	129252
	Professional		
	Hardware Engr	FY	129252
	Professional		
	Technician	FY	122143
	Graduate assistant		
	Grads.	AY	129099
		SS	24040

	Total salaries & wages		607609
	Grad fee remission		19800

	Total compensation		627409
B.	Fringe Benefits		

	Total fringe benefits		73501

C.	Total compensation and fringes		700910
D.	Non-personnel direct costs		
	7-8430 Travel - Domestic		7197
	7-8499 Other S & E		7023
	7-8998 Scientific Equip-New Robotic Arm		120000
	7-8998 Scientific Equip-Sensory System		115500

	Total non-personnel direct costs		249720
E.	Total direct cost		950630
F.	IDC		356974

G.	Total cost	$	1307604
			=======

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A Proposal on Automated Bridge Deck Construction

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Robert Cromwell
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Introduction

Recent studies carried out by a group convened by FHWA and NIST [FHWA] indicated that the automation of bridge deck construction would be highly beneficial. We believe that such automation could enhance productivity and efficiency by at least 30%. In this proposal, we will outline the steps that are ripe for automation. Given the diverse nature of the tasks involved, we believe that a consortium approach would be best for this project, hence the reason for the organizations and the principal investigators listed above. This consortium will work on the various aspects of an optimal automated screed. Purdue will address the sensory and mechanical problems associated with the flow and leveling of the concrete and with the inspection of the subdeck concrete. RPI, in conjunction with NCSU, will work on the automation of rebar handling and assembly. NIST will work on the higher-level integration aspects of the component technologies that will emerge from Purdue, RPI, and NCSU.

The SCREED Steps That Can Be Automated

[1] Inspection of the sub-grade to ensure all codes are met, including:

- (a) Adequate pads and spacers between beams and sub-deck panels.
- (b) Proper alignment of sub-deck panels.
- (c) Absence of cracks or voids in sub-deck panels.

[2] Laying of rebar, including placing the chairs and tying the rebar.

[3] Application of water and/or other agents as needed.

[4] Monitoring the flow of supplied concrete to ensure proper volume.

[5] Applying mechanical vibration as needed to ensure proper material flow.

[6] Monitoring the supplied concrete to ensure that standards regarding density and plasticity are continuously met.

[7] Monitoring the constructed deck extruded behind the machinery, to ensure internal and surface characteristics meet all standards.

It is possible that other operations, such as floating or tining, could also be included in the final system design.

Addressing these points in the order of operation, we see that inspection is the first step. This would most likely be visual inspection, and can be implemented as a combination of 2-D and 3-D visual sensing.[1] Cameras, possibly used in conjunction with structured-light sources, could be mounted on a gantry over the front of the machine. These sensors could ensure that the sub-deck panels are correctly aligned with the beams, that they are not cracked, etc. In the highly schematic Figure 1, the right-most gantry is shown as carrying out this task.

Mechanical arms on the front of the machine will be used to pluck rebar from a supply bin and place them on chairs, properly aligned. After the rebar is tied, further visual inspection will ensure its proper placement. Rebar assembly and tying would be done by the second of the linked gantries in Figure 1.

Water must be sprayed before concrete is poured, to avoid drawing too much water out of the mix. Visual inspection could ensure that all surfaces had been adequately wetted, driving the spray mechanism to correct any areas slighted.

We propose to use simple range sensors to determine the cross-section of the sub-decking as the screed progresses, and also to measure the cross-section of the supplied concrete. In Figure 1, structured-light projectors on the screed, coupled with cameras mounted on the second gantry, make these measurements. In this way the screed could ensure adequate supply, but no more, by communicating with the concrete supply devices. We believe that these material sources, probably concrete pumps in this case, can be linked into a site-wide packet radio network. A packet cluster architecture would allow random inter-machine communication between any two pieces of equipment on a site, as well as central control by a machine supplying a primary service. We have not attempted to show the actual concrete supply in Figure 1, since we feel that a flexible approach is required. The automated system we propose would communicate with whatever material supply systems were available, be that a conveyor system, a concrete pump, or whatever, to request concrete (and rebar) as needed.

Finally, as the integrated system progresses along the bridge, 2-D and 3-D sensors could inspect the finished product. The cross-sectional profile could be measured to a high degree of accuracy in order to ensure that all standards were being met. These measurements could form a record that would be available for later analysis. Also, the surface moisture characteristics could be monitored, and

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[1] While ultrasonics is used for detection of internal stresses and micro-cracking, it is perhaps ill-suited for this application.

corrected as necessary.

Automated Rebar Handling And Assembly

A major component of bridge deck construction consists of the handling, laying and tying of rebar to provide the reinforcement for the concrete deck. In current practice, rebar bundles are delivered to a job site and stacked for future use. Bundles are manually sorted and arranged at a staging site, transported to the bridge deck at the time of construction, and individual pieces are again handled manually for positioning and tying. Automation of these procedures would result in more efficient handling of materials, higher quality in the positioning and tying of the reinforcement, increased safety due to the reduced manual handling of heavy parts, and reduction in the incidence of back injuries resulting from bending and tying of the rebar.

Two major steps in this process may be addressed by automation techniques in order to achieve these goals:

(1). *Computer-aided design, organization and tracking of rebar materials:*

Rebar pieces should be bundled, delivered, and handled in lots which map directly onto the deck assembly process itself. Computer-aided design tools should be used to specify the rebar design and layout. The designer or construction process planner then specifies the order or layout and assembly of the rebar structure. Based on this order of assembly, the rebar pieces are specified as groups or kits, and this grouping is specified to the rebar manufacturer for delivery in the prescribed form with labels attached to the groups. This planning and labeling avoids rehandling and sorting at the construction site. Ideally, the delivery of the materials themselves would be coordinated with the construction schedule so that the rebar materials are delivered directly for layout and assembly of the deck and do not require separate staging. This delivery and assembly schedule is worked into the overall project plan to very the coordination of rebar assembly with deck pouting in the integrated deck construction system. Efficiency in transport, handling, and assembly is gained by careful planning and scheduling of the tasks.

(2). *Automated assembly and tying of the rebar parts:*

The assembly process itself will be integrated into the automated decking system which travels along the bridge and performs the tasks of rebar tying concrete pouring, smoothing and sensing in a single pass. The automated handling and tying of the rebar structure is a particularly challenging phase of this process. It is unlikely that general robot arms would effectively accomplish this task due to the length, flexibility, and weight of the rebar parts themselves. A more realistic scenario for rebar assembly is shown schematically in Figure (2), where manually assisted laying of the longitudinal rebar prepares the way for automated laying and tying of the transverse bars. The longitudinal bars are fed directly from a delivery vehicle or positioning in kits using a conventional crane. The manual operation sets the longitudinal bars on supports in their approximate final position. The first set of supports have built in physical spacers which align the ends of the bars with the prior set. The bar spacing for the remaining length will be set by the assembly and tying apparatus which tracks the longitudinal bars and adjusts their positions as it ties.

The transverse rebar placement and tying machine travels with the integrated decking system and is aligned to physical or optical guides along both sides of the bridge. The machine contains a feeder bin of transverse bars which have been loaded directly be crane according to the labelled groupings. Each transverse bar is fed and tied as the machine proceeds along the longitudinal bars. The longitudinal bars are tracked and positioning prior to tying. The proposed tying mechanism itself is a plastic "tie-wrap" loop analogous to ties which are used to secure cables and wires. Such a tie-wrap loop tightens securely and requires much less complexity in the automated Wing mechanism. The intersections of each transverse bar with all the longitudinal bars are tied simultaneously by a set of tie-wrap mechanisms. The details of the feeding, tracking, and tying mechanisms are not provided in this description, but have been developed to a stage of conceptual design. Specific attention is given to the need to hold and tie the transverse bars while the machine is in motion. An added feature of the integrated machine could include an inspection device to scan the resulting rebar mesh and confirm both correct geometry and placement of ties and supports.

The automated rebar installation system described here represents several innovations in the procedures and the mechanisms available for automated bridge deck construction. The impact of these innovations would occur as a result of both of these processes. Improvement in design and planning tools provide a direct link into the organization and handling of the rebar materials. This change would reduce the time required to handle the rebar and increase the safety of the workers. Eliminating the staging and sorting of the rebar materials could improve the efficiency of this phase of the project by as much as 50%.

The automated rebar laying and tying system would perform the rebar installation as a parallel operation with the concrete pouring. While the longitudinal layout would still be done largely with manual methods, the feeding and organization of the materials would be improved. The automated transverse bar assembly and tying would be entirely automated. Only the rebar feeder would need to be refilled as the task proceeded. This reduction in work. force and time required would increase the efficiency of this phase of the project by at least 50% and have additional benefits on health and safety issues.

The approach to rebar handling and assembly described here for bridge decking will impact other rebar assembly processes in road construction. Both the improved design and tracking approached, and the automated laying and tying devices can be adopted to other problems including center and sidewall construction and pilings. While the uniformity of the bridge deck problem suggests that it is particularly well-suited to automated technologies, these extensions to related areas will have similar benefits.

Performance Issues

What will be the productivity enhancement if such a system is deployed? A precise answer to that will depend on how many robotic arms and sensors are mounted on such a system. [On a wide span, like the one shown to us in Los Angeles, separate robot and sensor suites could be assigned to each 12 foot section of the deck.] Although admittedly a very rough guess at this time, even without any parallelism in robot arms and sensors, we believe that the proposed system would increase the productivity by at least 30%. Moreover, the quality of the decking would be superior, more consistent, and less prone to human error. This 30% figure is based on the manual observation of the current practice of deck construction in California. We observed the different cycles of interlocking steps that go into the process of laying down a deck and how, more often than not, the personnel assigned to one step have to stand around and wait while the other related steps are brought to completion.

Deliverables

Our plan is to carry out incremental automation of an existing machine for laying out bridge decks. This we believe will be the least-cost approach to gaining insights into the design of the various sensor systems that will be needed for the different automation steps. During the first year, we will develop the sensor system for monitoring the quality of the concrete deck laid out by the existing machine. The quality measures would be the uniformity of the height of the deck and of the uniformity of the texture of the surface. Both of these quality measures are evidently important and, in later phases of research, would be used to initiate remedial measures, such as the screed going again over the affected area after the concrete delivery system has either poured additional concrete over the area or scraped some of it off.

First year's effort will also result in the computerization of the design of rebar layouts and a system for the tagging of rebars so that, in the future, it would be possible to design a ''rebar feeder" that would automatically layout the bars. [Initially, this system of the future would require human assistance with the longitudinal bars.] The detailed mechanical design of an actual machine for laying out the rebars and tying them would require large engineering support and is not inclmed in this proposal.] Our first year's effort would only involve analyzing the feasibility of such a machine and testing the feasibility with computer simulations.

In the second year, we will develop the system for monitoring the volume of the poured concrete before it is leveled by the screed. For quality control, it is important that the volume of the concrete, poured initially into small heaps, is as tightly as possible in proportion to what is needed to fill up a certain area of the deck. Any large variation in poured concrete, especially when the amount poured is on the deficit side, manifests itself in the form of depressions that, with the current technology, have to be gone over manually and resmoothed by the motions of the screed. The development of the sensor system for monitoring the volume of poured concrete is expected to eliminate this manual intervention.

Another planned goal for the second year deals with analyzing, from kinematic and controls standpoints, the various alternatives for the rebar manipulation system. As a result of this study, we will be able to make definitive statements about minumum number of degrees of freedom that would be needed for laying down rebars. Of course, these conclusions would depend on assumed models for both how the bars are packaged and how the packages are delivered to the bridge deck.

The third year will focuss on the issues of integration of the component technologies developed in the first two years. This integration will allow us to simultaneously control the flow of concrete and do so in such a manner that the quality of the deck, in terms of the uniformity of thickness and texture of the surface, is ensured.

Budget Justification

The Purdue part of the budget includes 10% time for the PI, 25% in summer, and two graduate assistants. The budgets for RPI and NCSU have been included as subcontracts in the Purdue budget. Purdue has a policy of charging its overhead on the first $25,000 of a subcontract. The breakdown for the RPI budget is available and is as follows:

A Sanderson	(PI @ 10% + Summer)	=	$19,558
GRA's (2)	(AY Stipend/Summer)	=	32,776
GRA's	(Tuition)	=	24,422
Secretarial Assistance		=	2,355
Fringe Benefits		=	6,771
Travel		=	2,500
material, Supplies&Services		=	2,500
Indirect Costs (OH)		=	36,553

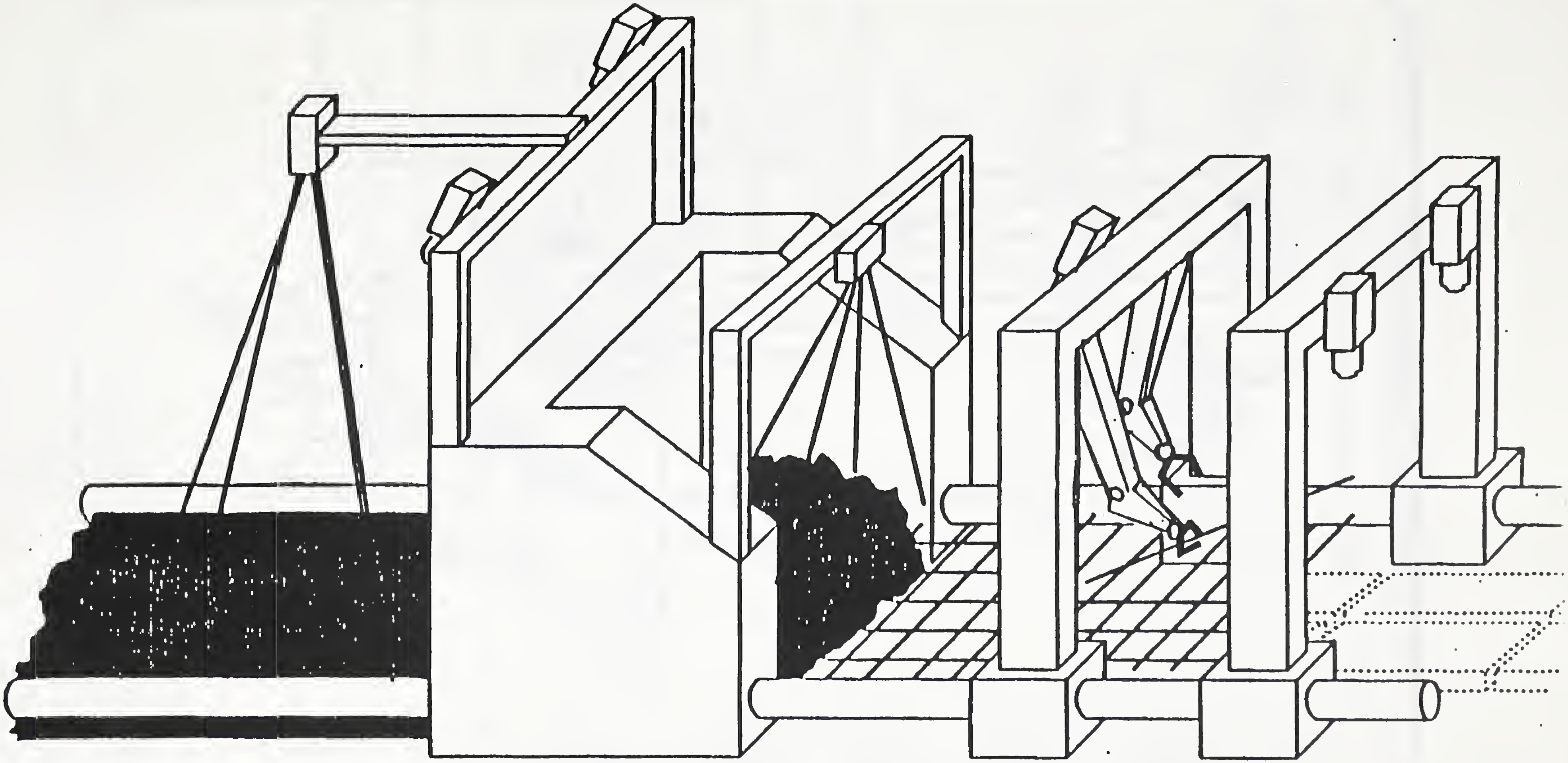
```
Total                                                =$127,435
```

The budget also includes a first-year request of $43,500 for building a shrouded structured-light sensing system that would work in an outdoor environment. This system will include a high-speed image processing system for grabbing multiple video frames and for video-rate low-level processing of these frames (cost: $33,000), two high-quality CCD color cameras (cost $3,000), multiple laser sources (cost: $2,000), two high-precision ball screws for the scanning machanism ($5,000), various and sundry components for mounting the lasers and cameras (cost $500).

References

[FHWA] The FHWA/NIST group report.

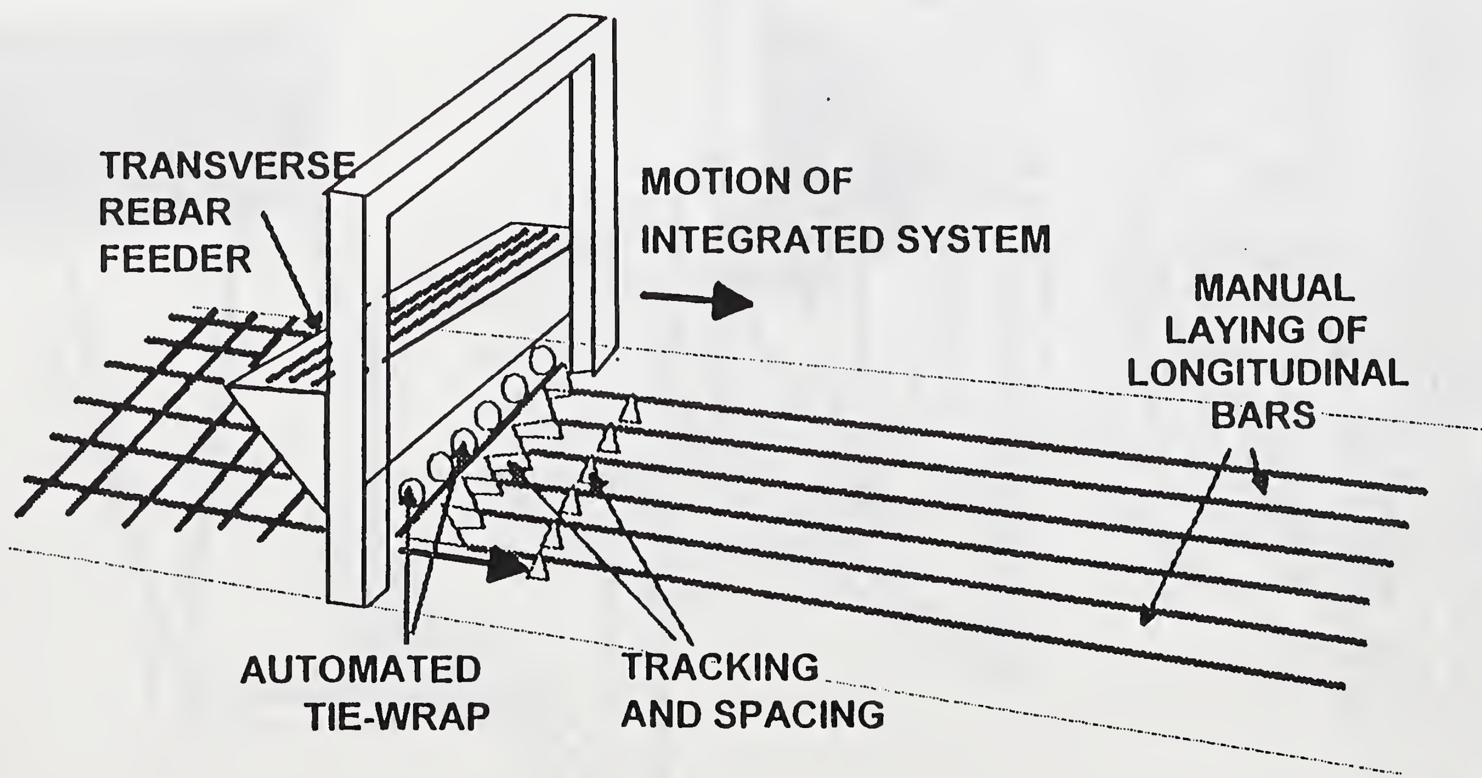
Concept Drawing for a National Demonstration Project For the Automation of Bridge Decking



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

Figure 1

CONCEPT DRAWING
REBAR ASSEMBLY APPARATUS
FOR AUTOMATED BRIDGE DECKING SYSTEM



Arthur C. Sanderson 5/19/93

Figure 2

PURDUE INTERNAL PURPOSES ONLY

For the period 01/01/1994 through 12/31/1994

A.	Salaries and Wages		
	1. Senior personnel		
	Faculty associate		
	A. Kak	0.10 AY	13212
		0.25 SS	9528

	Subtotal		22740
	2. Other personnel		
	Graduate assistant		
	Grads.	1.75 AY	41256
		1.50 SS	6900

	Total salaries & wages		70896
	Grad fee remission		6012

	Total compensation		76908
B.	Fringe Benefits		

	Total fringe benefits		7416

C.	Total compensation and fringes		84324
D.	Non-personnel direct costs		
	7-8430 Travel - Domestic		2000
	7-8499 Other S & E		1799
	7-8997 subcontract - RPI		127435
	7-8997 subcontract - NCSU		60000
	7-8998 Capital Equipment (see page 6)		43500

	Total non-personnel direct costs		234734
E.	Total direct cost		319058
F.	Indirect cost 0.510 of MTD cost		67377

G.	Total cost	$	386435
			=======

PURDUE INTERNAL PURPOSES ONLY

For the period 01/01/1995 through 12/31/1995

A.	Salaries and Wages		
	1. Senior personnel		
	Faculty associate		
	A. Kak	0.10 AY	14269
		0.25 SS	10290

	Subtotal		24559
	2. Other personnel		
	Graduate assistant		
	Grads.	1.50 AY	37131
		1.50 SS	7245

	Total salaries & wages		68935
	Grad fee remission		6582

	Total compensation		75517
B.	Fringe Benefits		

	Total fringe benefits		7872

C.	Total compensation and fringes		83389
D.	Non-personnel direct costs		
	7-8430 Travel - Domestic		2000
	7-8499 Other S & E		2926
	7-8998 subcontract - RPI		127435
	7-8998 subcontract - NCSU		60000
	7-8998 Capital Equipment (see page 6)		43500

	Total non-personnel direct costs		235861
E.	Total direct cost		319250
F.	Indirect cost 0.510 of MTD cost		41684

G.	Total cost	$	360934
			=======

PURDUE INTERNAL PURPOSES ONLY

For the period 01/01/1996 through 12/31/1996

A.	Salaries and Wages		
	1. Senior personnel		
	Faculty associate		
	A. Kak	0.10 AY	15411
		0.25 SS	11113

	Subtotal		26524
	2. Other personnel		
	Graduate assistant		
	Grads.	**** AY	34651
		1.50 SS	7607

	Total salaries & wages		68782
	Grad fee remission		7206

	Total compensation		75988
B.	Fringe Benefits		

	Total fringe benefits		8400

C.	Total compensation and fringes		84388
D.	Non-personnel direct costs		
	7-8430 Travel - Domestic		2000
	7-8499 Other S & E		1603
	7-8998 subcontract - RPI		127435
	7-8998 subcontract - NCSU		60000
	7-8998 Capital Equipment (see page 6)		43500

	Total non-personnel direct costs		234538
E.	Total direct cost		318926
F.	Indirect cost 0.520 of MTD cost		42008

G.	Total cost	$	360934
			=======

PURDUE INTERNAL PURPOSES ONLY

For the period 01/01/1994 through 12/31/1996

A.	Salaries and Wages		
	1. Senior personnel		
	Faculty associate		
	A. Kak	AY	42892
		SS	30931

	Subtotal		73823
	2. Other personnel		
	Graduate assistant		
	Grads.	AY	113038
		SS	21752

	Total salaries & wages		208613
	Grad fee remission		19800

	Total compensation		228413
B.	Fringe Benefits		

	Total fringe benefits		23688

C.	Total compensation and fringes		252101
D.	Non-personnel direct costs		
	7-8430 Travel - Domestic		6000
	7-8499 Other S & E		6328
	7-8998 subcontract - RPI		382305
	7-8998 subcontract - NCSU		180000
	7-8998 Capital Equipment (see page 6)		130500

	Total non-personnel direct costs		705133
E.	Total direct cost		957234
F.	IDC		151069

G.	Total cost	$	1108303
			=======

Construction Automation & Robotics Laboratory
North Carolina State University
Director: Dr. Leonhard E. Bernold

ROBOTIC EXCAVATION AND PIPE-LAYING

A Research Proposal
submitted to
The Federal Highway Administration

Submitted by
North Carolina State University
Department of Civil Engineering
Raleigh, NC 27695-7908
(919) 515-3677

November 1, 1993

TABLE OF CONTENTS

1. BACKGROUND AND MOTIVATION

1. 1 Background and Discussion of Related Research

Almost all production oriented robots today are utilized within the manufacturing industry. One main reason why true robots are hardly seen in the construction environment is because of the existing unstructured and complex conditions. In addition, construction mostly takes place in an uncontrolled environment, exposed to the weather, dust and noise. The attributes of the materials to be handled range from large, heavy, bulky, and non-homogeneous to light, fragile, and homogeneous.

Despite the many difficulties, opportunities for applying high technology in construction are abundant. For certain applications and situations, such as construction in hazardous areas (i.e., nuclear waste disposal, space construction), robotic technology is unavoidable [1]. However, applying high technology in these areas requires empirical as well as theoretical research.

Excavation of soil and rock is a high volume and repetitive construction operation. Some 30% of the earth's crust is shale or mudstone, much of which can be excavated by using a backhoe, front-end loader, or other heavy mechanical excavator. Because of their versatility, backhoe excavators are especially popular on construction sites. It is estimated that a fully automated excavating machine performing at 25% the efficiency of an expert human operator would be commercially feasible [2].

Studies on the applications of robotic excavation and robotic excavators have been undertaken by several researchers worldwide. Previous research results can be classified into three categories. The first category consists of work on geometric planning for robotic excavation. A few researchers have worked on gross specifications of digging [2, 3]. This type of planning abstracts the world into a geometric basis and does not take into account considerations of mass, force or any soil property. The entire excavation task is segmented into a sequence of geometrical shapes before excavation begins. The second category consists of work on controlling the robotic excavator along a planned trajectory. Here, different control principles and sensing technologies are proposed. Vaha studied and established a kinematic and dynamic control model for a robotic excavator [4]. Bullock and Oppenheim developed an approach for force-cognitive robotic excavation [5]. Tochizawa et al. reported about an automated excavator for excavating a trench for drainage using laser guidance [6]. The authors showed that the laser guidance helped to decrease the labor hours and increase the digging accuracy. Finally, there has also been some interest in remote controlled excavators (or teleoperated excavators) for construction and hazardous waste handling. The aim of this work is to remove the human operator from the immediate work site. Langreth reported about an advanced teleoperated hydraulic excavator [7]. This excavator operates with a master-slave control and incorporates the force-feedback control so that the human operator can not only control the mechanical arm very easily, but also "feel" the obstacles that the bucket hits. Provided with video images from three cameras, the operator sits remotely inside a building or a vehicle, manipulating and observing the operations.

1.2 The Hazards of Trenching and Pipe-Laying

The opening of trenches to bury sewer, water, and other utilities is an operation which can be observed on almost any highway construction project. Traditionally, a surveying crew will first stake out and mark the location of a planned trench. Later, a construction crew will begin excavating the trench to the desired depth using traditional surveying equipment and approximation to control depth and direction. Sometimes the stakes have been accidentally removed or damaged by the time the construction crew starts. Traditional excavation requires persons to enter the trench with shovels to even out the bottom, to lay pipe, etc.

The hazardous nature of construction work, especially that related to excavation work, is well documented. The fatality rate was estimated by OSHA at 50.8 deaths per 100,000 workers per year for 1984-1988, whereas for construction work generally, it was estimated at 24.8 deaths per 100,000 employees. Similarly, trenching cave-in fatalities have been estimated by NIOSH at 75 per year, and lost workday injuries due to cave-ins at 1000 per year. In a recent report prepared by NIOSH, based on OSHA's inspection data, it was estimated that at least another 97 persons were killed as a injury among construction workers, including those doing excavation work, is about two time the all industry average (i.e., 15.1 injuries per 100 workers in construction compared with 7.7 injuries per 100 workers in all industries) [8].

The major occupational hazards of excavation work result from cave-ins, from exposure to underground utilities, and from material or equipment falling into the open trench. Precautions against cave-ins include bracing, sloping, benching, use of shields, and freezing. However the proper use of these techniques requires an understanding of the importance of such factors as excavation depth and width, soil type, hydraulic pressure, and other specific conditions present at the worksite.

1. 3 Scenario of Laser Guided Robotic Excavation

Providing a technology which would eliminate or sharply reduce the time a worker has to spend in the trench would be of great significance to construction safety. This research project proposes to use the available laser guidance technology to provide a means to automate trench excavation. Figure 1 depicts an overview of the trench digging operation using laser guidance with a real excavator.

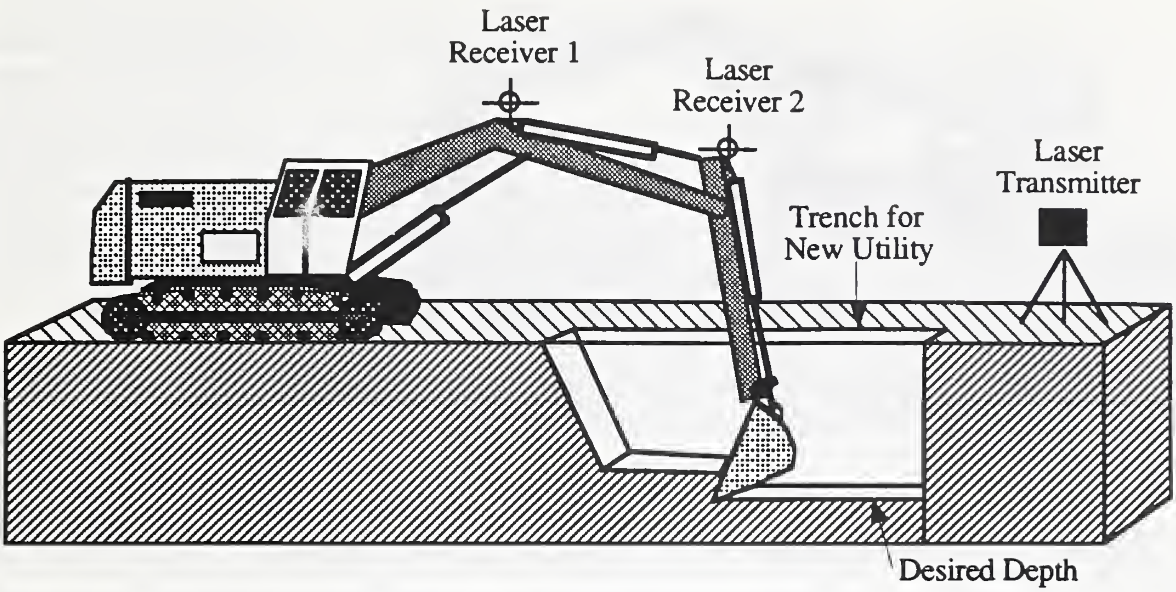


Figure 1. Proposed Trench Excavation Using Laser Guidance

The proposed research project would investigate the effectiveness of the laser guidance positioning approach in assisting the trenching operation by eliminating: 1) surveying before and during the operation, 2) risky exposure of workers in the trench during the operation, and 3) labor intensive hand shoveling at the bottom of the trench.

1. 4 Scenario of Laser Guided Robotic Pipe Laying

The proposed experimental work on robotic pipe laying is another application for laser guidance technology in the construction area. A conceptual overview of the envisioned future of laser guided pipe laying is shown in Figure 2. The final goal here is to improve the accuracy and efficiency of pipe laying. Laser beams and laser planes will be used as the calibration and measurement tools.

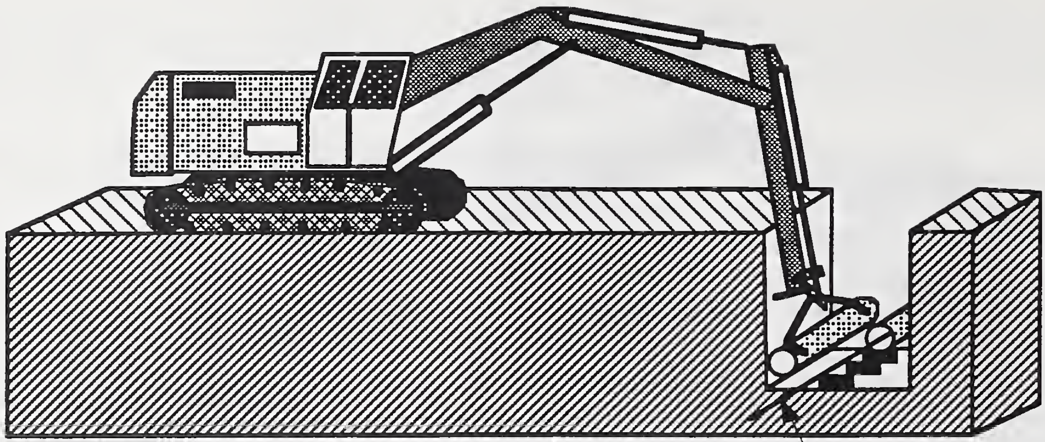


Figure 2. Concept of Robotic Pipe Laying by Laser Guidance

1.5 Basic Premises of Robotic Excavation and Pipe Laying

1) Advanced sensing devices directly mounted on the excavator boom allow not only the electronic detection of position of the manipulator and forces within the manipulator and the hydraulic power system but also the detection of metals (e.g., pipes) and possibly other buried material which should not be damaged. The sensory system has the flexibility to be interfaced with on-board equipment monitoring devices (e.g., oil temperature) as well as CAD software providing data related to the trenching and/or pipe-laying operation (e.g., depth of trench) and electronic maps of underground utilities. These technologies would eliminate the need for crew members climbing into the hazardous trench. Also, many costly accidents due to the damage of buried utilities will be avoided.

2) Shared control between the operator and an intelligent and sensor based controller. Feedback of bucket position and encountered obstacles to the operator in 3-D. Presentation of virtual views of obstacles or positions which are presently not available to the operator. This operator augmentation technology will make the entire operation more efficient.

3) Real time position control through feedback from local positioning systems as well as laser guidance systems such as traditional beam and rotating plane lasers. This would eliminate the need for staking out the trench and possible delay of operations because of lost or dislocated stakes. The operator of the equipment would be supported by visual targets on a screen and actual positions for either robotic or manual control of trenching and pipe-laying operations. The control system also supports the automatic generation of as-built data to be directly fed to an electronic utility map.

4) Support of smart end-effector attachments which are able to connect themselves to the excavator boom/bucket without the need for detaching the bucket. Quick disconnects allow for easy hook-up of both electronic cables and hydraulic power. The smart end-effector for the laying of pipes includes a set of specialized sensors, such as a laser receivers, that are directly integratable with the overall sensory system. The pipe-manipulator-attachment is capable of automatically grabbing, positioning, and joining the pipes for storm drain or sewer lines (using o-ring joints) supported by a remote positioning system (e.g., laser).

1. 6 The State-of-the-Art Experimental Research Facility at NCSU

A prototype robotic backhoe excavator has been built within the Construction Automation and Robotics Laboratory (CARL) of North Carolina State University (for complete description, see Appendix A). This robotic manipulator is designed to serve as a platform for many different applications such as soil excavation, pipe laying, rock breaking, etc. Figure 3 shows schematically the experimental robotic excavator. Many different end effectors (i.e., bucket, gripper) can be mounted at the end of the arm to reassemble this device into different experimental configurations. In this figure, the manipulator is equipped with a bucket to operate as a computer controlled backhoe excavator. The two joy stick controllers also allow shared, traded, and distributed controls. This robotic manipulator has a reach of 6 meters (16 feet) with heavy lifting capacity. It is driven by one hydraulic motor and three hydraulic actuators (cylinders) which provide a total of four-degree-of-freedom (DOF). Each hydraulic line is equipped with an electronic pressure transducer. Most recently, a vision system has been added to allow remote operation in shared, traded or distributed mode.

One 386 personal computer is used to control the entir robotic manipulator and to collect data from the sensors in real time. Two A/D data collection boards and a D/A control board act as interfaces with the electric transducers and hydraulic actuators. Several sensors have been mounted for different tasks. The joint encoders are used to measure the individual joint displacements during excavation. Accelerometers mounted on the boom and the stick provide data about the accelerations as well as the inclinations. In order to detect an underground obstacle such as a rock, one load cell has been mounted between the rod and the clevis of the actuator driving the bucket. To detect metal pipelines, one metal detector search coil has been installed and tested on the excavator arm (see Appendix B). Its present capabilities allow also contour mapping of obstacles as a basis for deciding about effective methods of removal (if appropriate).

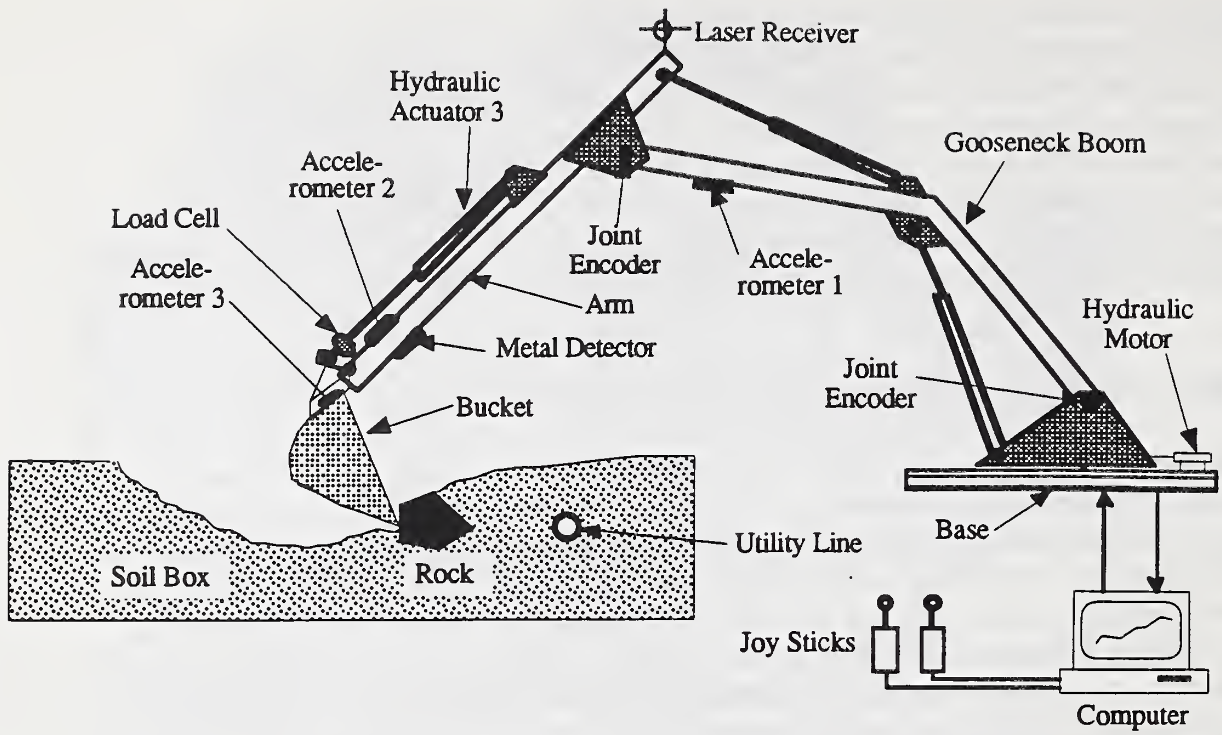


Figure 3. Experimental Facility For Robotic Backhoe Excavation

2. STATEMENT OF RESEARCH OBJECTIVES

Researchers in CARL have worked for some time on studying and developing a robotic backhoe excavator (see Appendix A). The goal is to create a system which will be more accurate and efficient than traditional excavators by retrofitting already employed backhoes with automated controls. While this work is still ongoing, the laboratory is interested in developing new technologies and finding new applications in the area of construction automation. The proposed research project is organized into two phases: A) Laboratory Experimentation, and B) Field Testing. The two phases are further broken down into various workpackages.

Phase A) Laboratory Experimentation:

Workpackage A.1: Mechanical Hardware
Workpackage A.2: Sensor Systems
Workpackage A.3: Controls
Workpackage A.4: System Integration and Operator Interface

Phase B) Field Testing:

Workpackage B.1: Field-Hardening of Prototype Systems
Workpackage B.2: Field Testing in Training Ground
Workpackage B.3: On-Site Field Demonstrations

The overall objective of the research project is to develop a prototype system that will be able to demonstrate the technology in the field and provide a basis for designing a marketable system in the future. Several intermediate objectives have been identified.

Objective 1. Proof of the technical feasibility to robotically excavate trenches based on information from a CAD database. It includes avoidance of non-removable obstacles, such as buried non-metallic pipes.

Objective 2. Testing and verification of the already developed arm-mounted metal detection system under field condition.

Objective 3. Assessment of the speed and accuracy of laser guided robotic excavation of trenches in the field.

Objective 4. Assessment of the speed and accuracy of laser guided pipe-laying in the field.

Objective 5. Development and evaluation of human-machine interfaces to provide an effective operator interface.

3. RESEARCH PLAN

A.1: Mechanical Hardware

Design and development of necessary hardware attachments to upgrade the existing experimental research facility. Because of the advanced state of the existing system this effort will concentrate on the pipe-laying hardware and its hydraulic manipulation system. The mechanism will be able to handle a variety of different pipe sizes.

A.2: Sensor Systems

Several important sensing capabilities have already been tested. They include: a) position sensing for excavator within the construction site, b) position sensing for bucket, c) force sensing systems for excavation, d) force sensing systems for pipe-laying, e) arm-mounted metal detection system, and d) position and force sensing for joining pipes. The main addition to the already existing sensing system are the spatial positioning system for guidance and for direct integration with a CAD representation of trench and pipe. Such a system will also allow the establishment of as-built infomation automatically. Several spatial positioning systems are on the market (e.g., CAPSY by Spectra-Physics) while new ones are under development. It is proposed to purchase one of those systems to be integrated with the excavator hardware shown in Fig. 3.

A separate effort will concentrate on the full development and field testing of the metal detection technology. With the help of a company that manufactures metal detectors for the construction industry, a prototype metal detector search coil has already been mounted on the excavator arm. Figure 4 presents the schematic of the presently deployed system.

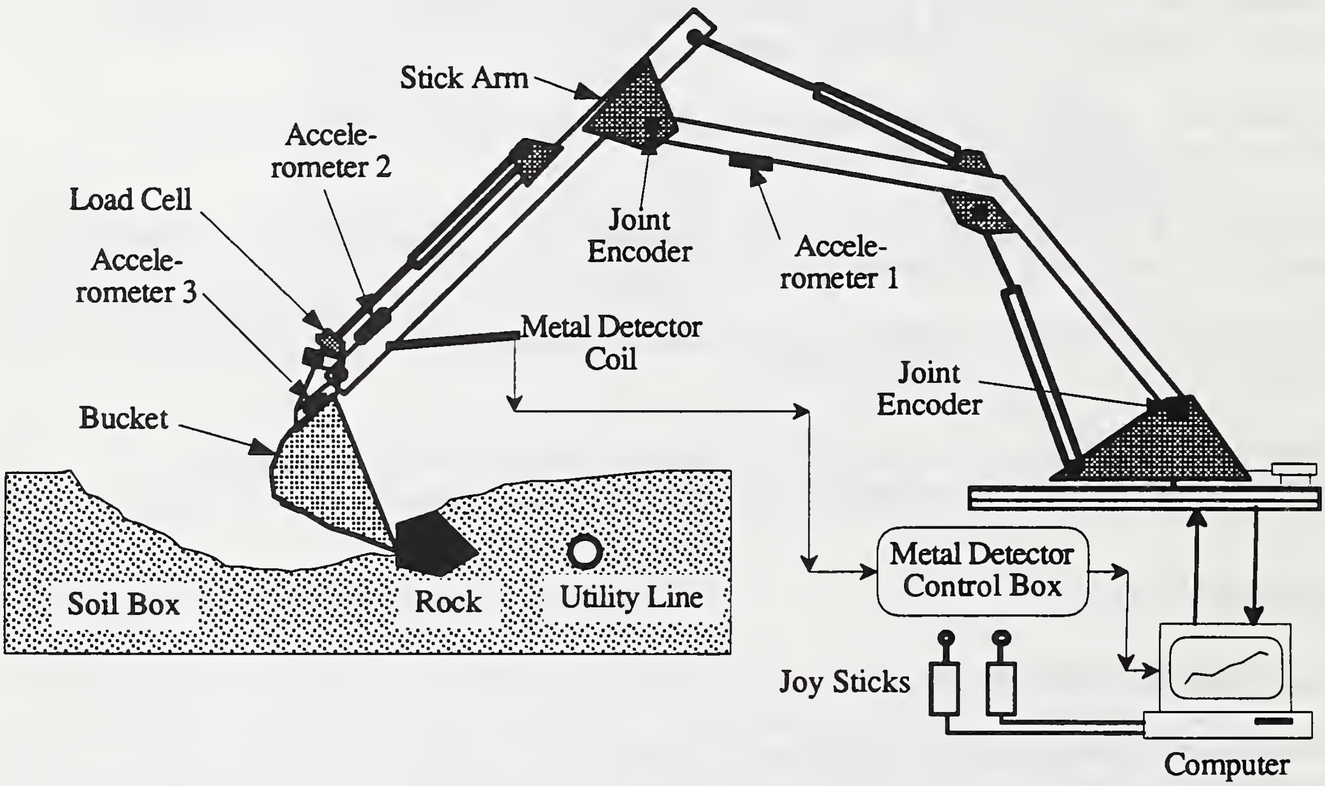


Figure 4. Schematic of the Arm-Mounted Metal Detection Hardware

As shown, the active search coil assembly, which has not yet been optimized, is directly mounted onto the excavator arm. Different from passive metal detection systems, this method does not require any additional hardware. Preliminary tests have demonstrated that the system, that is directly integrated with the computer, is able to provide sufficient sensory data to detect metal pipes. Extensive experimentation and tests will be conducted to verify the accuracy and effectiveness of the system. The work would include experiments in different soil conditions (e. g., wet) and with different metal objects. The final product would be a prototype device that could be mounted on traditional excavators, would warn operators about the existence of any buried metallic obstacle and would indicate the position of the obstacle in front of the excavator bucket. If successful, such a system could be directly implemented in the field as an attachment.

Pipe laying requires accurate measurements and fine adjustments. It is envisioned that through the use of laser guidance and electric controls, pipes of different sizes can be positioned efficiently and accurately. Figure 5 depicts a laboratory experiment for pipe laying using laser guidance.

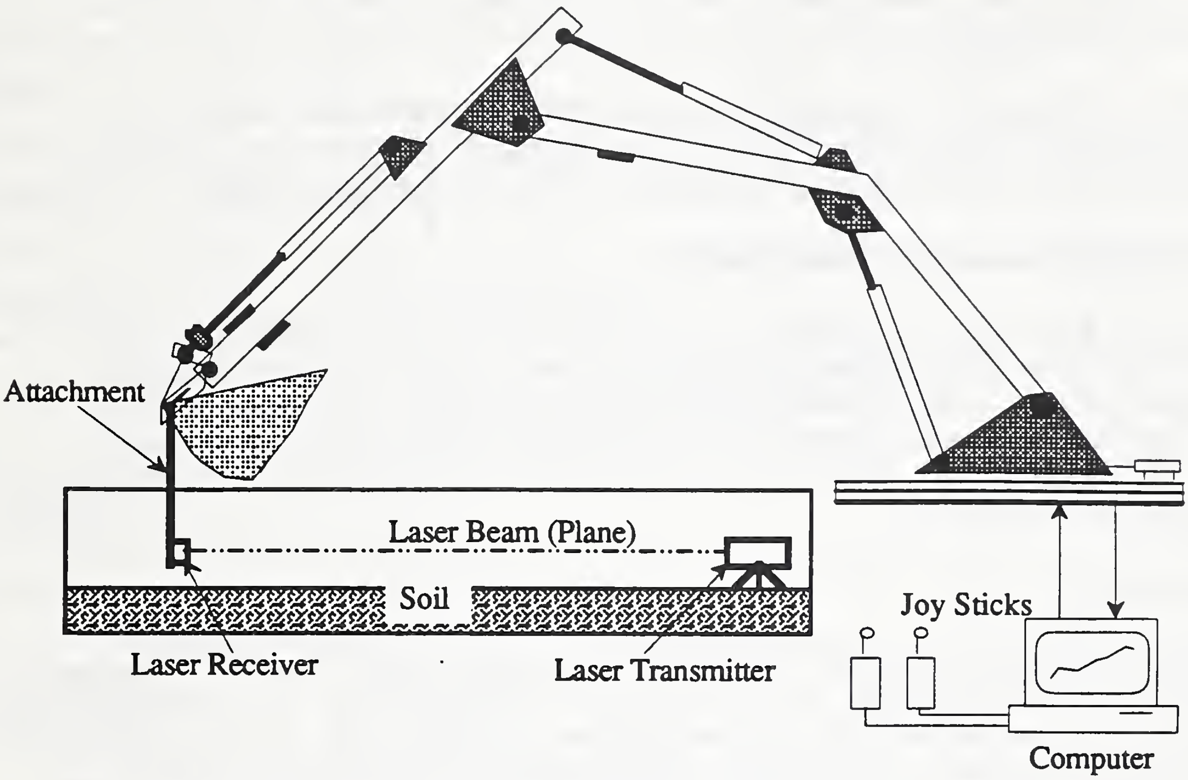


Figure 5. Experimental Laboratory Set-Up For Laser Integrated Control

The availability of laser guidance together with the mechanical means to manipulate and connect drainage pipes with o-ring joints will eliminate the need of workers in the trench. At the same time, laser systems already provide very precise guidance needed to put the pipes in place accurately. Total integration of this technology with the existing robotic manipulator in the laboratory and in the field will be the focus of this sensor system.

A.3: Controls

This work package will focus on the development of control models and control laws that provide the necessary algorithms for executing the different tasks and subtasks within a fully integrated framework. For that purpose, an extensive list of experiments will be conducted as a basis for establishing a basis for adaptively controlling the manipulator. Due to the unstructuctured environment of soil excavation, obstacle recognition, pipe handling, etc., different control methods have to be tested and verified (e.g., neural networks). In addition, virtual reality will be used in order to enhance the sensory based information of the environment (e.g., approximate location of a pipe). The main task is to design a control software which has the capability of letting the manipulator follow a planned trajectory and adjust its path through sensing feedback. Because of existing underground obstacles, such as metal pipes and rocks, the control system should also be able to develop methodologies for robotic obstacle detection, obstacle surface mapping, and automatic handling for underground objects. Preliminary research work has already been conducted in CARL.

Similarly, control methods for gripping, manipulation, positioning, and joining of large concrete pipes with o-ring joints will be developed. Effective use of sensor systems (e.g., force) and the human capabilities of an operator will be critical.

A.4: System Integration and Operator Interface

CAD databases, sensory systems, and control models for the different tasks, organized in modules, will be integrated into an overall control structure. Because of the importance of creating user-friendly human-machine interfaces, special attention will be given to develop operator consoles for on-board and remote controls. Many important lessons will be learned from studying and testing different interaction schemes.

B: Field Testing

The work in phase A will be followed by field tests with large size excavator equipment. For that purpose, the developed technology will be modified and "hardened" to survive the construction environment. Subsequently, the hardware and software will be mounted on a rented (possibly loaned) excavator to be tested on a training ground. In a later phase, the robotic system will be field tested in cooperation with the North Carolina Department of Transportation and contractors affiliated with the Construction Automation and Robotics Laboratory.

4. PROJECT SCHEDULE

Year 5	Year 1	Year 2	Year 3	Year 4	
8 10 12	2 4 6 8 10 12	2 4 6 8 10 12	2 4 6 8 10 12	2 4 6 8 10 12	2 4 6
Mech. Hardware	xxxxxxxxxxxxxx				
Sensor Systems	xxxxxxx	xxxxxxxxxxxxxxx			
Controls		xxxxxx	xxxxxxxxxxxxxxxxx	xxxxxx	
System Integration and Operator Interface				xxxxxxxxxxxxxx	
Field-Hardening				xxxxxxx	
Field Testing in Training Ground					xxxxxx
On-Site Field xxxxxxx Demonstrations					

Possible start-date: July 1994.

5. RESOURCES AND BUDGET

Table 1: Resource Allocation and Sources of Support

Resources	Phase A Laboratory Exp. (3.5 Years)	Phase B Field Testing (1.5 Years)	Total
2 Principal Investigators	$ 100,000	$ 45,000	$ 145,000
Research Associate	$ 90,000	$ 40,000	$ 130,000
Graduate Res. Assistants	$ 150,000	$ 80,000	$ 230,000
Fringe Benefits	$ 40,000	$ 17,000	$ 57,000
Travel	$ 9,000	$ 7,000	$ 16,000
Tuition Remission	$ 35,000	$ 15,000	$ 50,000
Electronic Equipment	$ 8,000	$ 20,000	$ 28,000
Computer Hardware		$ 10,000	$ 10,000
Vision System		$ 8,000	$ 8,000
Pipe Laying Endeffector Att.	$ 10,000	$ 2,000	$ 12,000
Small Equipment Supplies	$ 5,000	$ 5,000	$ 10,000
Excavator Rental		$ 9,000	$ 9,000
Equipm. Transportation		$ 5,000	$ 5,000
Spatial Positioning System	$ 20,000		$ 20,000
Laserplane Grade Control	$ 2,000	$ 2,000	$ 4,000
TOTAL	$ 469,000	$ 265,000	$ 734,000

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4 P. Vaha, "Modelling and Control of Cognitive Excavation," Technical Report, School of Civil Engineering, Purdue University, West Lafayette, Indiana (1990).

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Automating Bridge Inspection and Maintenance

Ken Goodwin
Bob Bunch
Robot Systems Division, NIST

September 30, 1993

Bridge inspection and maintenance offers a significant opportunity to reduce costs through automation, while achieving enhanced environmental control. The current situation with respect to bridge maintenance is in fact so severe that many states cannot afford to attend to all of the bridges in need of repair, and are focusing only on the most severe cases. In consequence, any potential cost savings could be expected to contribute directly to public safety by extending available funds to repair increased numbers of bridges. A 1991 report from the Federal Highway Administration (FHWA) notes that 40% of the bridges on the federal aid system were built in the 1950s and 60s with minimum cover for reinforcing steel and no corrosion protection.

More than a quarter million bridges are eligible for federal aid. Of these, FHWA estimates that 75,000 need work. In addition to Federal funding, state and local governments spend between $500 million and $1 billion a year on 1,500 to 2,500 bridges that receive no federal money. All levels of government combined will spend more than $4 billion a year on bridge maintenance.

Increased environmental regulations have resulted in delayed maintenance, particularly in the stripping and repainting of highway overpass structures. Increased process restrictions and media waste disposal costs have been the primary cause of delays and additional costs. Environmental regulations now require the isolation of blast areas and have significantly increased waste disposal costs, especially for paints containing hazardous wastes such as lead. In past years, a contractor could remove an overpass's coating system through open air blasting. However open air blasting produces airborne contaminants which are harmful to personnel, equipment, and the environment. Workers must now operate equipment in limited visibility containment areas while wearing cumbersome protective suits. Containment areas are constructed with scaffolding and are enclosed by tarps.

The erection of the containment area is a slow and expensive process which adversely affects productivity. A North Carolina Department of Transportation case study of the stripping and primer application of two bridges in 1991, found that 50% of the time in a typical work day was spent moving and sealing the containment enclosure and cleaning and vacuuming debris.

The automation projects proposed in this document would address these needs with a series of near-term and longer-term developments. Automated systems would remotely inspect bridge paint condition and the physical state of bridge members, erect shrouds, recover stripping media and paint with increased efficiency, and in general, reduce the manpower and time required to strip and paint an overpass. A simple teleoperated system would provide the following key benefits:

- Increase speed and efficiency of inspection operations.
- Reduce time required for placement of shrouding.
- Reduce time required to strip paint.
- Reduce exposure of workers to harmful materials.
- Reduce environmental impact of paint stripping.
- Reduce hazardous waste through stripping media recycling.
- Reduce hazardous waste through more efficient paint application.
- Improve quality of painting and decrease time required for application.
- Automate generation of maintenance and inspection databases.
- Reduce manpower requirements.

For typical highway overpass bridges, it appears feasible to reduce the costs of stripping and painting by one quarter to one third, while also providing environmental advantages.

1 Approach

Technology is available, or nearly available, today for automating the remote collection of imaging and other sensor data to assess bridge and paint condition. Similarly, automated tooling for stripping and applying paint is available. The principal problems to be addressed are the automated placement and manipulation of such sensors and tooling, the automated placement of shrouding, and ultimately the automated interpretation and logging of data and control of operations.

An initial, near-term, step is to develop improved alternatives to "Snoopers" for positioning and manipulating automated bridge inspection and maintenance operations. Advanced control techniques, already developed for industrial robots, could be used to provide coordinated motion for devices adapted from existing machines, such as aerial lifts or cranes. Two such concepts are presented in this proposal for the development of a prototype Robotic Highway Overpass Stripping (RHOS) System. These devices could begin to achieve a number of real benefits, even with initial simple teleoperated modes of operation.

To the extent possible, NIST intends to borrow from technology being developed for advanced paint removal processes in other industries and apply it in the development of a RHOS system. NIST recently completed an investigation of current DoD and civilian efforts aimed at automating paint stripping of both aircraft and Navy vessels.

An effort is underway within the Armed Services Joint Depot Maintenance Program called the Joint Paint Removal Study. Under this effort, five lead depots have been designated for projects aimed at developing alternative stripping processes. As is the case with bridge stripping, the DoD requirements are driven by environmental regulations. The DoD efforts will encompass the development, testing, and in some cases, automation of alternative stripping processes.

NIST anticipates involvement in the DoD program through the application of the NIST Real-time Control System (RCS) technology to the development of a coordinated motion boomlift. This telerobotic aerial lift will then be integrated with paint blast, media recovery and recycling equipment now being developed. The project will result in the development of a prototype telerobotic machine for ship hull paint stripping in Navy ship yards. The goal is to use as much standard, or off-the-shelf components as possible to produce a productive and reliable system at a low cost.

Much of this technology would also be applicable to bridge stripping. Although the configuration of lift equipment chosen for bridge maintenance may differ from that used for ship hull stripping, much of the control software and hardware would be applicable to both. For example, a mobile platform-mounted lift is anticipated for use in ship hull stripping, whereas, the use of a truck-mounted articulated lift might be a likely candidate for bridge maintenance. However, this would require only slight variations for the implementation of an RCS. In addition much of the technology that is now being developed for processing equipment under DoD projects would also likely be applicable to the maintenance of bridges.

Initial efforts for a bridge maintenance automation project would be focused toward the development of a coordinated motion aerial lift or truck crane. A teleoperated prototype machine would be produced that is controlled via a joystick using intuitive inputs on the part of the operator. The operator would simply move the joystick in the direction in which he desired the equipment (e.g. stripping or painting head) to move.

In the longer term, wholly-new forms of robotic devices could be designed for delivery of many inspection and maintenance services. Such machines would be programmed from databases containing descriptions of each bridge along with its associated maintenance requirements. These databases would constitute the input for planning and scheduling bridge repair, and for programming the robots to perform various functions such as inspection, paint stripping, and repainting.

Advanced robotic devices working from such databases could be developed to crawl along over and under bridges, automatically performing routine inspection, paint stripping, and repainting chores. While large bridges might have custom-designed, dedicated robots, robots might also be specially designed for whole classes of smaller bridges. Such robots would be transported to bridge sites and deployed to crawl along a bridge and associated support structures and monitor a number of parameters to monitor the health of the bridge. Physical characteristics that could be monitored include; macro-scale deformations, paint condition and corrosion. The same robots, while still in place and fitted with different apparatus, would then perform stripping, painting, and perhaps minor structural repair as indicated by the inspection.

2 Near-Term Technical Objectives

Bridge inspection and maintenance is a major activity involving numerous bridges and overpasses ranging widely in both size and complexity. A variety of automation opportunities appear as alternatives to the current use of "Snoopers" and scaffolding for manual operations.

The NIST Robot Systems Division has been developing flexible, intelligent control systems for over a decade. The foundation of these control systems lies in a control architecture which establishes a skeletal framework for building flexible controls for complex systems. This sensor based, NIST Real-time Control System (RCS) architecture has been implemented in numerous robot, vehicle, and factory control applications. These systems include serial link robots, cooperative robots, coordinated robots, factory automation, automatic guided vehicles, autonomous underwater vehicles, teleoperated robots, teleoperated vehicles, and parallel link manipulators.

The Robotic Highway Overpass Stripping (RHOS) system could overcome many of the environmental barriers confronting highway overpass maintenance. RHOS would be an integrated set of manipulators, stripping devices, and containment shrouds under the coordinated control of an RCS system. RHOS would provide rapid set up and use, complete recovery of the blast media and paint debris, maximum recycling of the stripping media, and the exclusion of human workers from the blasting environment.

An overpass stripping operation using RHOS would consist of a robotized aerial lift capable of manipulating a blasting nozzle and a containment shroud along the structural members of highway overpasses. The containment shroud would transport media waste to a recovery system. The recovered blasting media would, to the extent possible, be recycled.

The goal of this near-term demonstration-effort would be to develop and demonstrate a robotically manipulated paint stripping system. This RHOS system would consist of a robotized aerial lift capable of manipulating blasting nozzles and containment shroud along structural members of highway overpasses. RHOS would initially be largely teleoperated and would be designed for ease of operation by current overpass maintenance contractors. The operator interface would be designed to minimize the operator's programming tasks and support on-site diagnostics. The RHOS system would include an integral shroud subsystem, expected to recover a minimum of ninety five percent of the spent media and chip debris. The shroud subsystem will also transfer the debris to a recycling subsystem. RHOS would clean overpass metal structures to near white metal by media blasting, and produce an appropriate surface profile for new coatings. In its initial form, the RHOS system should be able to access those surfaces routinely addressed by manual blasting.

2.1 Technical Approach

Development of the RHOS system will require two major efforts. One effort will focus on the development of a computer controlled aerial lift to maneuver in and around highway overpass structures. The second effort will focus on the development of the processing equipment which includes all blasting, containment, and recovery subsystems.

Initial efforts for the bridge maintenance automation project would be directeded toward the development of a coordinated motion aerial lift or truck crane. A teleoperated prototype machine would be produced that is controlled via a joystick using very intuitive inputs on the part of the operator. The operator would simply move the joystick in the direction in which he desired the equipment (e.g. stripping or painting head) to move. Currently available aerial lifts are not capable of making a smooth coordinated move, such as moving in a straight line along the surface of a bridge girder. Each joint must be controlled independently by the operator.

NIST has held discussions with major aerial lift manufacturers about establishing a Cooperative Research and Development Agreement (CRADA) in which a coordinated motion aerial lift would be jointly developed between NIST and one or more lift manufacturers. Following a rapid development period, this prototype could be duplicated in low-cost production versions for use in common maintenance operations.

Subsequent implementation of higher levels of the RCS control hierarchy, along with sensory feedback would provide increased autonomy of this equipment, resulting in higher productivity and greater cost savings. This effort would also provide a foundation for the automation of other similar equipment, providing additional benefits to the FHWA in other operations.

These initial efforts would entail interface developments for additional mechanical joints and command, status, and sensor communications. Efforts would also include the development of computer, electronic, and sensor components needed for robotic control with minimal operator interaction. The RHOS system controller will supervise both the aerial lift and the processing equipment. NIST would develop the controller in accordance with the NIST Real-time Control System architecture (RCS) including an easy-to-use operator interface, such that the operator will require neither specialized computer nor robotic training. The RCS hierarchal structure would ensure the RHOS control system remain readily adaptable to future expansion.

Existing systems for acquiring sensory data and for maintaining camera fixation through coordination of camera motion with lift motion could easily be adapted to RHOS. NIST has already developed rapid camera gaze-control systems operating under the RCS.

Concepts for two potential containment systems are depicted in Figure 1 and Figure 2. The containment system must permit manipulation by the robotic aerial lift, must not restrict the blasting of overpass structural members, and must transfer the media waste to the recovery subsystem. The containment system must also conform to irregularities on the surface to be stripped in order to insure adequate containment of the waste. This may entail multiple modular shroud components designed for rapid change or a single conformable device. Deployable shrouding might begin with a large emplacement within which the robot mechanisms could act over a large volume, as shown in Figure 1.

Subsequently, new developments from DoD efforts might be adapted to provide small, movable shrouding as shown in Figure 2.

Final system integration will entail the assembly, testing and demonstration of the complete RHOS system. The system integration phase of the project would conclude with field demonstrations of the RHOS system, in which various overpass structural members would be stripped.

2.2 Major Tasks

Twelve tasks are proposed for the RHOS project. This initial tasks (1-6) could be accomplished over the first 12 months, with a demonstration of the retrofit coordinated motion manipulator, possibly performing an inspection operation. The remaining tasks (7-12) would be completed in 24 months. Actual bridge stripping would be demonstrated using a prototype teleoperated stripping machine. The project tasks are briefly outlined below.

1. Identify Overpass Features: Through cooperative efforts with the Federal Highway Administration and a State Department of Transportation, select a representative set of highway overpasses. The effort will identify common features or families of features from the selected overpasses which now require periodic stripping. The RHOS system will then be developed to process all of the identified features.

2. Select Lift/Crane: Perform comparative analysis of available lifts and cranes. All configurations of commercially available lifts and cranes will be evaluated for use in this project. Several characteristics will be considered, including dexterity, cost and suitability to coordinated motion/teleoperation development.

3. Select Blasting System: Perform comparative analysis of available paint removal methods. Commercial equipment is currently available for several different stripping processes. Additional processes and blast media are also under development in DoD and private industry. These processes will be evaluated for use in bridge stripping. To a great extent, this evaluation will be based on results obtained from previous efforts, such as the DoD Joint Paint Removal Study.

4. Develop Shroud Subsystem: The shroud subsystem is considered to be the highest risk element in this project. The shroud must fulfill the EPA requirements for level 3 paint stripping by recovering the spent media and debris, and transfering this material to the recycling subsystem. An evaluation will be conducted of existing and emerging shroud and recovery system designs. Efforts will be made to incorporate demonstrated technologies into the design of the RHOS shroud subsystem.

A stationary-type shroud design would remain fixed to the bridge structure while the blasting nozzle maneuvers within (see Figure 1). In this configuration, some of the manipulator joints operate within the shroud while others remain outside. The shroud will have a port which will seal about the manipulator and ensure its freedom of motion. Media waste will exit the shroud through another port primarily by means of gravity and be routed to the recycling system.

With a dynamic shroud design, the shroud would be an integral part of the end effector carrying the blasting subsystem (see Figure 2). This form of shroud would enclose the blasting unit and move along a surface via the robotic aerial lift. The dynamic shroud system would most likely consist of interchangeable modules, each designed for use on different structural features. A vacuum system would route the media waste to the recycling subsystem. A shroud such as this will be tested in a Navy ship hull stripping demonstration project. In addition, a small company has demonstrated a similar prototype recovery system for ship hull stripping.

5. Select Computer Configuration: Perform comparative analysis of computer hardware for control system. Select system based on availability, support, ease to interface, expandability, convenience of field maintenance, and cost.

6. Retrofit Lift/Crane: The commercial lift or crane chosen for the project must be at least partially retrofitted to accommodate coordinated joint motion control. This will include implementation of joint position sensors, either resolvers or encoders. It will also require that all joints be driven via electrohydraulic proportional control valves having sufficient frequency response to allow for the necessary level of system performance. In addition, some re-routing or installation of new electrical and hydraulic cables will also be required and it may be beneficial to implement the control and power lines on a commercial bus network.

7. Design Manipulator Extension: Standard aerial lifts do not have sufficient dexterity to access all of the required areas of an overpass. Additional degrees of freedom (joints) will be incorporated at the end of the aerial lift to provide the necessary manipulator dexterity.

8. Develop User Interface: The operation of the RHOS system will require minimal training for existing overpass maintenance personnel. The controls shall be intuitive with clear identification. The interface panel will also be portable such that the operator will be able to position himself at the most advantageous position to operate the system.

9. Develop System Controller: A set of routines will be developed in the system controller to perform all the functions required of the RHOS system. Routines

will be included which provide for the stripping of specific overpass features and collections of features, and also for performing diagnostics and simple maintenance.

10. Integrate Aerial Lift and Extension: This integration consists of assembling mechanical components, establishing controller communications, and establishing the coordinated motion.

11. Integrate Stripping System: The stripping system shall be tested to ensure that the blasting subsystem can remove common overpass paints and that the recovery subsystem contains and recycles the media as required. Representative values will be derived from these tests and used to establish the system's operating parameters. These parameters include such items as media flow rates, pressures, stand-off distances, linear feed rates, and overall processing rates.

12. Perform Field Tests: The final testing includes two phases. The first phase could be conducted at NIST. The RHOS system will be operated at the extremes of its design requirements. Tests will ensure the robustness of the controller, the thoroughness of the programming, and the convenience and completeness of the operator interface.

The second phase will consist of stripping paint from girders at one or more highway overpass sites. The sites will be selected by an appropriate state highway department. The site should be scheduled for routine paint stripping maintenance and the regular contractor's employees should operate the RHOS system.

3. Longer-Term Technology

Advanced robotic devices will be designed with the ability to perform inspection, paint stripping, and repainting operations by maneuvering along the I-beams under existing bridges. An example of such a robot is illustrated in Figure 3. This device consists of two crawling manipulators (arms) and a work platform with a robot manipulator and containment shroud (shroud not shown in the figure).

3.1 Advanced Automation

The initial test version of this device will function under teleoperation via an operator using a joystick or space-ball. However, a programmable system will have an control system that will retrieve geometry information from a database describing the particular bridge as well as a set of actions for performing prescribed tasks. The bridge database will be developed originally from an "as-built" database, which in turn will be updated each time the bridge is repaired or otherwise modified. This database will provide the input for planning and scheduling bridge repair, as well as for programming the robot to perform the various functions required for inspection, paint stripping, and repainting.

The design envisioned would operate under the guidance of a hierarchical control system, such as the NIST RCS design. The controller would retrieve database information describing details of a particular bridge, and adapt subsequent operations under a generic task plan that would be applicable to all bridges of the that same class. This would be a straightforward extension of current state-of-the-art industrial practice. For example, in the robotic welding of automobiles, new CAD designs are accessed to generate paths for robot welders. Since the nature of operations in the field is inherently less structured and less controllable than in factory situations, this level of operation would still require general guidance by an operator, but routine, detailed motion planning in real-time would be generated by the task-planning program.

In a later stage of development, the device would incorporate sensing for guidance in addition to the initial, specialized sensing for inspection. This would allow the machine to adapt to errors in positioning and to new situations not contained in the data base (e.g., bird's nests, undocumented repair work).

Sensory-guided robotic systems of this sort, operating under general task plans and working from apriori databases exist today in laboratory settings and experimental operations. They can successfully adapt simple planned operations such as navigation and manipulation to minor discrepancies between their observed sensory data and expectations generated from a priori databases. Experimental approaches to automatically updating the databases from the robot's sensory input also exist. The bridge-maintenance task presents an attractive target for applying and extending these experimental technologies to highway maintenance operations due to the relatively fixed nature of the task, the relatively structured environment, and the relative ease with which working databases could be produced.

4.0 Estimated Cost

NIST has held discussions with aerial lift manufacturers regarding the development of a coordinated motion machine. It is anticipated that a CRADA will be established between NIST and at least one of the manufacturers in which a manufacturer would contribute the use of a lift for the duration of this project. The following is an estimate for the cost of this proposed project, assuming the manufacturer contributes the lift.

Phase I - Develop Inspection Capability (12 months):

1.	Identify Overpass Features	$ 20,000
2.	Select Lift/Crane	15,000
3.	Select Blasting System	20,000
4.	Develop Shroud Subsystem	70,000
5.	Select Computer Configuration	10,000
6.	Retrofit Lift/Crane	80,000
		$215,000

Phase II - Develop and Demonstrate Paint Stripping (24 months):

7.	Design Manipulator Extension	30,000
8.	Develop User Interface	35,000
9.	Develop System Controller	65,000
10.	Integrate Aerial Lift and Extension	30,000
11.	Integrate Stripping System	35,000
12.	Perform Field Tests	40,000
13.	Document Results and Transfer Technology	40,000
		$285,000
	Total	$500,000

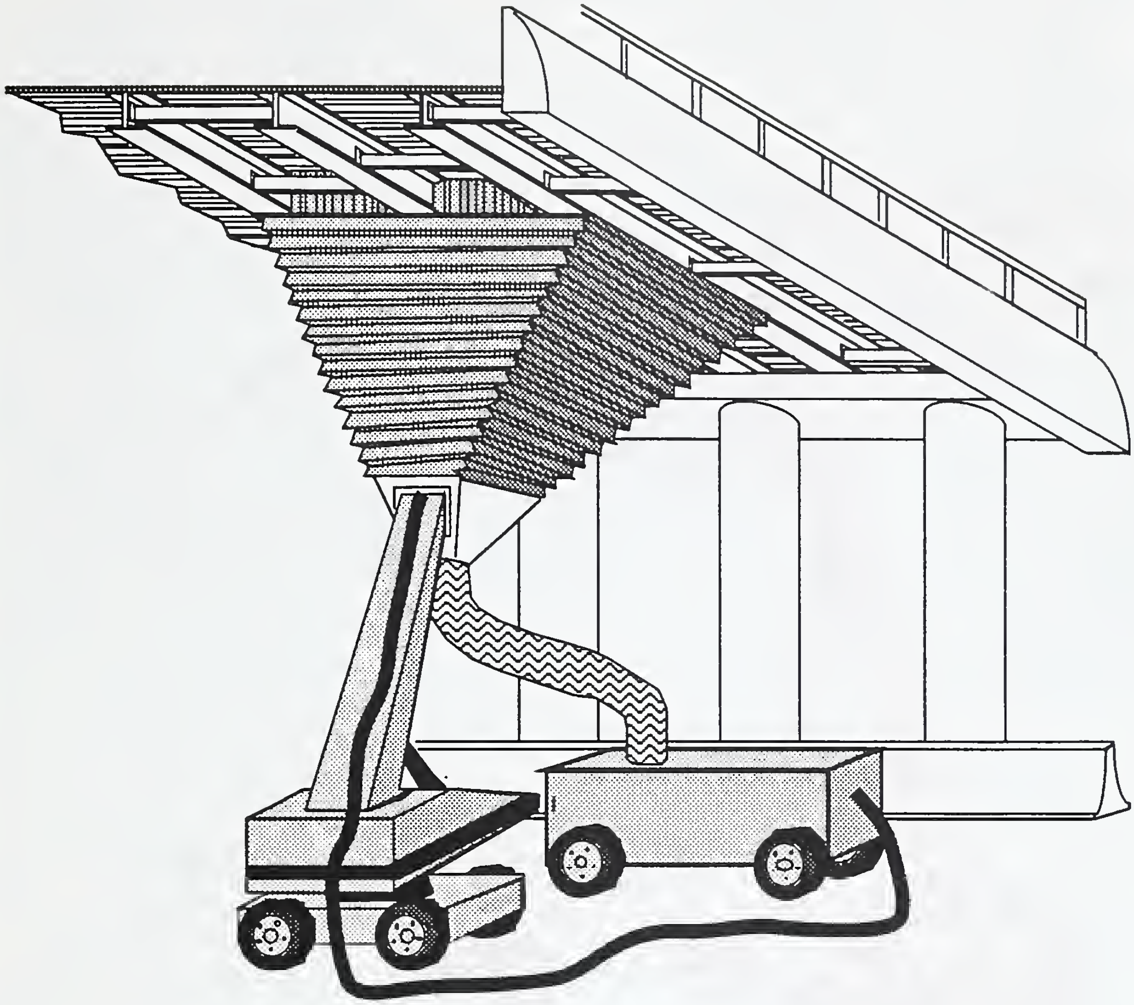

Figure 1. Possible Stationary Shroud Configuration

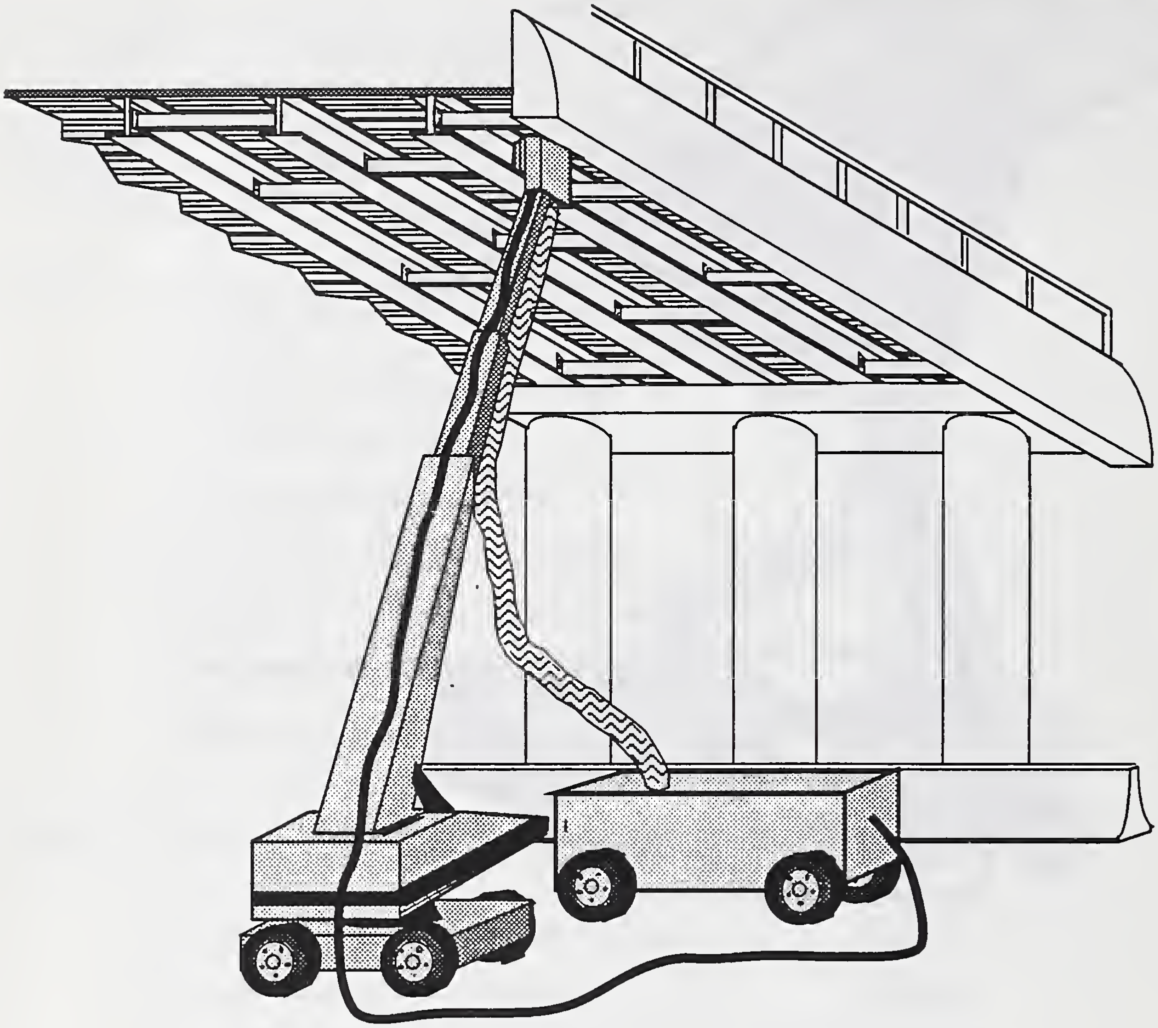

Figure 2   Possible Dynamic Shroud Configuration