GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. E-20-603 (R5839-0A0) GTRI/GIT DATE 10 / 1 / 84

Project Director: Drs. Daniel Halpin and Roozbeh Kangari School/~~Lab~~ Civil Engineering

Sponsor: National Science Foundation

Type Agreement: Grant No. CEE-8319498

Award Period: From 9/1/84 To ~~2/28/87~~ 12/31/85 (Performance) 5/31/87 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$ 144,654	$ 144,654
Funded:	$ 144,654	$ 144,654

Cost Sharing Amount: $ 9,003 Cost Sharing No: E-20-322 (F5839-0A0)

Title: "Robotics Feasibility in the Construction Industry"

ADMINISTRATIVE DATA

OCA Contact Lynn Boyd X4820

1) Sponsor Technical Contact:	2) Sponsor Admin/Contractual Matters:
Gifford H. Albright	Sharon Graham
Division of Civil & Environmental Eng.	Grants Official
National Science Foundation	National Science Foundation
1800 G Street	1800 G Street
Washington D.C., 20550	Washington D.C., 20550
(202)357-7710	(202)357-9626

Defense Priority Rating: n/a Military Security Classification: n/a

(or) Company/Industrial Proprietary: n/a

RESTRICTIONS

See Attached NSF Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT

COMMENTS:

Includes usual 6 month unfunded flexibility period.

COPIES TO:

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Accounting	Research Communications (2)	Other A. Jones

FORM OCA 4:383

GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 5/14/86

Project No. E-20-603

School/~~Lab~~ CE

Includes Subproject No.(s) N/A

Project Director(s) Halpin-Kangari

GTRC/~~GIT~~

Sponsor National Science Foundation

Title - "Robotics Feasibility in the Construction Industry"

Effective Completion Date: 12/31/85 (Performance) 3/31/86 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [ ] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
- [XX] Final Report of Inventions -Questionnaire sent to P.I.
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ____________________

Continues Project No. ____________________

Continued by Project No. ____________________

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Project File
Other Jones, Embry

Form OCA 58:1004

II. RESULTS FROM PRIOR NSF SUPPORT

1. Name of Institution: Georgia Institute of Technology
2. Names of Principal Investigators: Daniel W. Halpin
   Roozbeh Kangari
3. Grant NO. CEE-8319498/Amount: $144,654
4. Starting Date: 1 September 1984
5. Completion Date (anticipated): 31 December 1986
6. Grant Title: Robotics Feasibility in the Construction Industry
7. Summary of Progress to Date:

A summary of progress based on the major items in the original proposal schedule is given in the sub-paragraphs below. In effect, all items scheduled for work during the first year have been commenced and satisfactory progress has been achieved.

7.1 Identification of High Return Items

Workshops with professionals were conducted to discuss potential construction operations for robotization and identify candidate processes for robotization. These workshops were held at Georgia Tech and summary information regarding the workshops is given in NSF Annual Progress Report NO. CE-8319498. The purpose of convening these workshops was to discuss the concepts of automation and robotization with practitioners in the field and get feedback from industry concerning possible areas for automation.

The following classifications were used for characterization of candidate operations for automation and/or robotization.:

(1) Dangerous, hazardous, and tedious operations
(2) Operations requiring a high level of precision
(3) Operations with high potential for production improvement
(4) Operations with potential for cost improvement
(5) Operations which utilize craft expertise which is vanishing
(6) Operations with a high potential for restructuring and innovation

Special attention was given to the identification of hazardous construction work tasks. Mr. Mendoza, a graduate research student, conducted a study to identify the major hazardous operations suitable for robotization. As part of this study, he developed an evaluation technique for establishing the level of hazard based on OSHA requirements and permissible exposure limits. Details of this study are presented in Reference 4 of the Annual Progress Report.

7.2 Analysis of Standard Technologies

Ongoing work is directed towards modeling and analysis of standard technologies using CYCLONE simulation techniques. The objective of this work is to study standard work sequences at the micro task level (i.e., work activities with duration of minutes or hours). This operation was selected since it is repetitive, requires precision, and can be boring. It has been robotized by several Japanese firms and this study will hopefully help identify what attracted researchers in Japan to develop prototypical equipment to handle this process. Several other operations to include rebar fabrication and rebar placement have been automated to a high degree and will also be modeled. Operations such as grinding, sand blasting, and bush hammering, as well as pavement breaking and similar demolition activities are being considered for study.

7.3 Extension of Existing Studies Using Video-Tape

Video tape studies have been made of several processes and evaluation of the work sequences involved is in progress. Processes which have been video-taped for the purpose of study include:

(1) Rock quarrying
(2) Concrete block laying
(3) Steel member fabrication
(4) Pile Driving
(5) Poured-in-place concrete barrier wall construction
(6) Reinforced earth retaining wall construction

Reduction of these processes to work task sequences for the purpose of identifying tasks with a high potential for automation/robotization is being accomplished.

7.4 Microanalysis of Motions

Functions of robot control vary according to the complexity of the work task involved in the process. A complex work task is viewed by the robot control as a group of primitive tasks which need to be processed in order to finish the complex task. Figure 1 shows the relationship between these primitives and the corresponding level of robot sensory control.

The motions to be performed by a robot constitute a complex work task. High level vision sensors reduce complex tasks to a set of simple ones. These in turn are further broken down into elemental moves by intermediate vision processing. Elemental moves are the movements required by the different parts of the robot to process a given task.

These elemental moves are at a level subordinate to the work task as defined in Halpin and Woodhead (Reference 8 of Annual Progress Report). Methods-time measurement (MTM) concepts are being used to analyze these motions for high potential work tasks with high automation potential.

7.5 Development of Evaluation Technique for Ranking High Potential Work Tasks

An evaluation technique based on expert systems will be developed. Preliminary study of various expert systems has already started. Utilization of microcomputer expert programs such as Insight Knowledge Systems Vers. 1 and 2 from Level Five Research, and the Deciding Factor, as well as other programs on mainframe (LISP) has been investigated.

The evaluation techniques based on these programs will combine the expertise of the parties involved in the construction industry. The results of workshops on robotics will be translated to production rules in order to establish an expert knowledge base. Then, the results will be combined with an algorithmic model which estimates cost, profit return, and production of the operation. Utility value analysis will be considered whenever sufficient information is not available.

The final result of this model will be a set of recommendations about a given construction process which describes whether it should be robotized. A confidence level will be associated with each outcome. Necessary suggestions to improve or further automate a construction process will be provided. The methodology is designed to quantify qualitative judgements on the part of an expert group, and to combine that with the results of an algorithmic model which estimates cost and production.

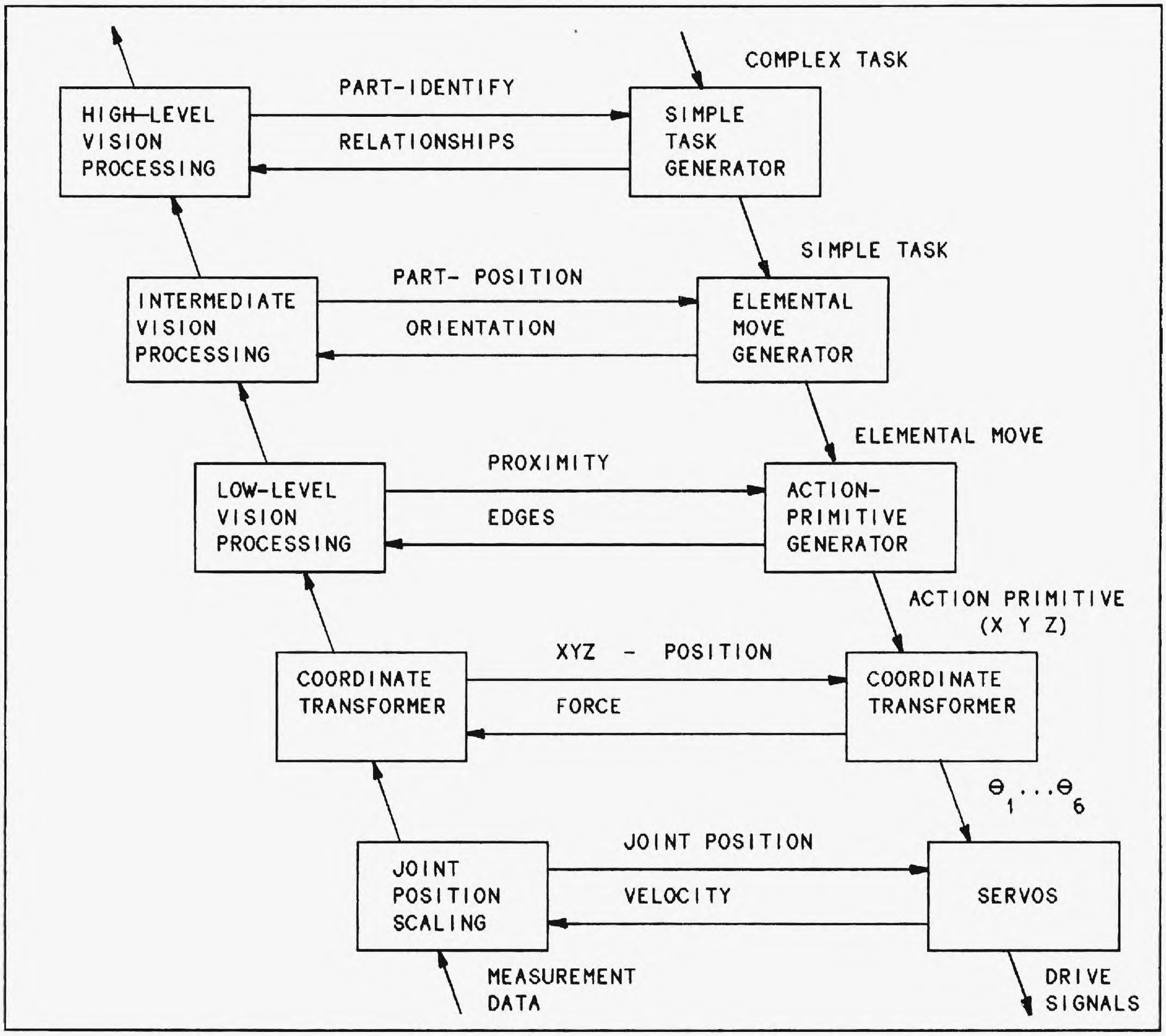

Figure 1. Relationship Between Primitive and Robot Control

II. PROJECT DESCRIPTION

A. INTRODUCTION

In most industries, experts are the key to success. This is no where truer than in the construction industry. One of the most salient characteristics of this industry is that the knowledge to run the business rests with a few key individuals who have gained their expertise through long years of experience.

Below the level of these experts, are individuals with varying degrees of experience and knowledge. In the construction industry, members of this lower level group tend to be somewhat transient. They come and go with a frequency which makes keeping an acceptable level of knowledge a constant challenge for management.

An additional characteristic of the construction industry is that most often, experience counts for much more than detailed technical knowledge. For example, it is more important for field personnel to know what actions will avoid future problems than to have a sophisticated engineering background. Further, meaningful knowledge and experience in construction field operations is frequently gained by trial and error or by listening to the advice and counsel of experts.

Another characteristic of this industry worthy of note is that it is project oriented. That is, the complexity of construction undertakings requires a team approach because no one person has all the answers, or remembers all the necessary detail, or has the requisite experience.

The postulation of these characteristics is intended to argue that the construction industry operates in an environment where knowledge is scarce. It is an environment where solutions to problems depend on the problem solver's judgement and experience which evolved into a set of heuristics or rules-of-thumb. It would be desirable, but undoubtedly impractical, to have the company's most experienced problem solvers on call to consult with the field management team when needed.

However, recent advances in the field of artificial intelligence have created new opportunities for making expert knowledge available to those who need it. In particular, a branch of artificial intelligence termed "expert systems" currently occupies the attention of many researchers including those in the construction field.

Expert systems are knowledge-based computer programs which attempt to emulate the performance of an expert who is reasoning within a relatively narrow topical area or domain. The knowledge base contains the heuristics which represent the problem solving process of the expert.

B. SCOPE OF RESEARCH

Objectives

The main objective of this research is to extract, articulate, and codify a knowledge base representing the problem-solving heuristics of an expert in construction field operations. This knowledge base is expected to provide a better understanding of construction field knowledge, leading to the establishment of basic principles and methods of operation.

A sub-objective of this research is to enhance the knowledge base by including existing algorithmic submodels and data bases. For example, the expert might need data on the effects of concrete additives, volume and quantity tables, soil compaction data, etc.

A final, important objective is to report the results to the academic, research, and industrial communities. We hope to expand research collaboration among academic and industrial experts in construction leading to the establishment of a Georgia Tech research group in construction automation. This group would operate in conjunction with the Computer Integrated Manufacturing Systems already at work at Georgia Tech.

Domain

For the purposes of this research, construction projects can be thought of as two distinct but overlapping phases: planning and execution. The planning phase embodies all those decisions which need to be made at the macro level before starting work. This phase includes the selection of major construction technologies, mobilization of major items of equipment, and development of the construction schedule. The execution phase includes all those decisions at the micro level necessary to implement the plan. Typical decisions in this phase include how to allocate resources, how to react to changing weather conditions, how to coordinate competing trade subcontractors, and what safety precautions are necessary.

To further illustrate the distinction between planning and execution: the construction schedule provides a relatively broad outline on the sequence and duration of activities to achieve project goals -- it is not typically intended to be a work plan for field use. For example, an activity on the project schedule might be mobilization. The field force is then charged with the responsibility for generating a work plan and configuring resources to accomplish the mobilization activity on the project schedule.

We do not wish to overemphasize this point, but we feel it is important to differentiate between planning and execution to put our proposed research in the proper perspective.

The area of interest of this research will be the execution phase of construction field operations. It is further proposed to limit the scope of inquiry to the mobilization, foundations, and structural phases of the project. These activities are usually on the critical path of a project schedule and the foundations and structure are high risk operations which impose a premium on judgement and experience.

The individual we will focus on is the field superintendent who has reached the status of expert. These are individuals who have gained their experience and refined their judgement through many years of practice. They use a heuristic approach to problems rather than an algorithmic approach. Their knowledge is relatively scarce and in demand. And, their decisions have a significant impact on the outcome of the project. Thus, the expert superintendent acting as micro planner and problem solver is the proposed candidate for the development of our knowledge base.

Moreover, we will limit our investigation to the building sector of the construction industry in lieu of other sectors such as heavy or residential or industrial construction. The building sector ranges from commercial office towers, government buildings, hospitals, universities and churches to light manufacturing, warehousing, and retailing facilities.

Our focus on the building sector is motivated by several factors. First, this sector typically accounts for up to 40 percent of the construction economy (29, 30). Second, it is anticipated that experts will be readily available from this sector in the Atlanta area. Finally, it is expected that the knowledge base created from this sector could be transferable to other sectors with slight modification.

To summarize, the domain of the knowledge base will be the decision-making process of the field superintendent in the mobilization, foundation, and structural phases of a project in the building sector of the construction industry. These boundaries are believed, at least initially, to form an appropriate envelope for the scope of the knowledge base.

Knowledge Representation

It is noted that the research will be limited to developing only the knowledge base of an expert system. Figure 1. shows the relation of the knowledge base to the total expert system. Although it will be necessary to use an existing expert system package to test and evaluate the knowledge base, the other elements of the system will not be a subject of this research.

Knowledge is the information that an expert system must have to behave intelligently. As noted previously, we are particularly interested in the type of knowledge which could extracted from the field superintendent in the mobilization, foundation, and structural phases of a project.

Of the three most common ways to represent knowledge (production rules, frames, and semantic nets), this research will use a production rule based system. Production rules are a formal way of specifying

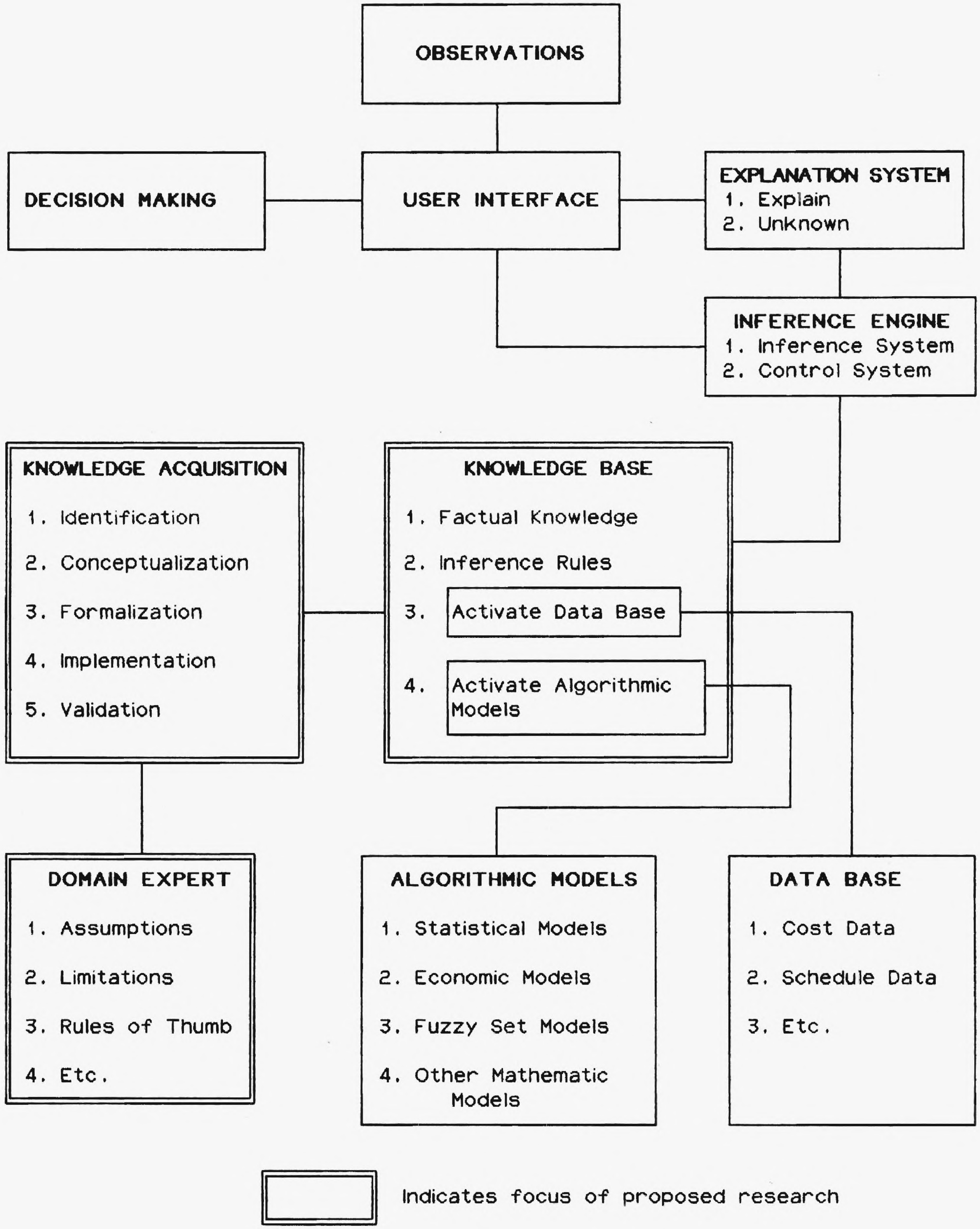

Figure 2. Expert System Architecture

how experts review conditions, consider various possibilities, and recommend action. These rules are expressed as

IF (premise) THEN (conclusion)
or
IF (condition) THEN (action) statements.

A typical rule might be:

RULE:	For backfill crew assignment
IF:	Backfill area is closely confined on two sides
OR:	Backfill area is sloped > 45 degrees
AND:	Backfill area is < 200 square feet
THEN:	Use two man team with portable compactor when backfill is scheduled

We expect to be able to classify the collected knowledge in the following ways:

1) Planning Knowledge
2) Debugging Knowledge
3) Diagnostic Knowledge
4) Predictive Knowledge

Planning knowledge helps decide on a course of action before acting. Examples of this type could be the knowledge to create a plan for resource allocation, or the knowledge of how to schedule trade contractors in a congested space, or the knowledge of what type safety netting to provide.

Predictive knowledge infers likely consequences of situations. Examples might be the effect of adding to crew size in an effort to increase productivity as opposed to lengthening the crew day, or likely consequences of various types of embankment supports, or the consequences to weather on recently poured concrete.

Debugging knowledge finds solutions for malfunctions. Examples could be the knowledge of options to dry out the excavation for a foundation or the knowledge on how to improvise when needed materials are not available, or the knowledge on how to solve an interference problem between trade contractors.

Diagnostic knowledge infers the causes of malfunctions. Examples of this category would be the knowledge of why a concrete finish failed, or possible causes of why the window mullions are out of alignment, or possible sources of water infiltration in a foundation wall.

This classification should allow us to better understand the nature of the knowledge in the defined domain. Other classifications may suggest themselves during the knowledge gathering phase.

C. Expected Significance

The knowledge base generated by this research is intended to be a first step toward retaining the expertise of senior individuals in the area of construction operations. This knowledge base would be expected to serve as a springboard for use by practitioners in the construction industry, by educators in the academic community, and by researchers in artificial intelligence laboratories.

Practitioners would have a knowledge base available for use which could improve productivity, minimize false starts, and enhance safety. Educators would have a basis for injecting an element of realism in courses relating to field operations. We would expect this research to be a first step at establishing a global knowledge base for use by researchers in areas of simulation, decision making, estimating, and scheduling. Conversely, the global knowledge base could serve to incorporate research by others in the areas mentioned above. Finally, this research could lead to new insights in the planning and operation of construction projects.

D. Relation to Longer-Term Goals Of Investigator's Research and to Related Work Under Other Support

Preliminary work on the application of knowledge-based expert systems in construction has been undertaken at Georgia Tech by both principal investigators. Work has been done to establish a resource of knowledge about construction operations. Professor Kangari offers a graduate course in expert systems in construction and various domains in the construction area have been extensively documented. Professor Riggs offers a course in simulation of construction and process operations and continues to build on a rich library of information about site operations. This research is expected to complement and draw from these existing libraries.

Related work under other support includes Professor Kangari's research in the application of robotics to construction operations and Professor Riggs' work in cost and schedule control.

The long-term goal of both investigators is to remain active in the automation of construction operations especially in the knowledge-based expert systems and robotics area.

E. Relation to Present State of Knowledge

Expert systems have been developed to solve many different types of problems. In the field of chemistry, one successful example of expert system development is DENDRAL. This is an innovative research project for determining the topological structure of organic compounds. MOLGEN is another application of expert systems in the field of chemistry. This program assists in planning gene-cloning experiments. Other expert system research work in this field includes inferring molecular structure, synthesizing organic molecules, and planning experiments in molecular biology (40).

Expert system research work in computer systems is typified by XCON, one of the first and most successful systems of this type. XCON configures computer components. Additional expert system work in computer systems includes fault diagnosis, chip configuration, and manufacturing control (23).

Expert system research work in geology produced PROSPECTOR, a system designed to assist geologists estimate the probability of finding certain types of mineral deposits. Current expert system research work in geology includes oil-well log analysis and fault diagnosis related to drilling operations (25,44).

MYCIN was an early example of expert system research work in medicine. MYCIN helps physicians diagnose and treat infectious blood diseases and is now being used for research and training. Current expert system work in medicine includes interpretation of medical test data, disease diagnosis and treatment, and instruction in medical diagnosis and management techniques (16,33,37).

Military uses of expert systems have included interpretation of sensor data, battlefield assessment analysis, weapons allocation, and tactical planning (40).

Expert system research work in Civil Engineering includes developing a knowledge based consultant for structural analysis, analysis of large finite element networks, damage assessment of existing structures. Additional examples of expert systems in Civil Engineering are management of water resource problems, computer aided design and drawing, diagnosis of automated mass transit systems, interpretation of cone penetrometer tests, and geotechnical characterization of sites. In recent years, expert systems have been used in the following construction related areas: pump repair, well selection, structural design, change order evaluation, quality quality control, scheduling, claims analysis, and construction robotics (38).

Generally, these systems use a knowledge base to operate at the expert's level. They solve complex and difficult problems which require the knowledge of an expert and their performance depends critically on the use of facts and heuristics.

This proposed research will concentrate on the preliminary work to develop a knowledge base similar to ones used by the expert systems described above.

F. Relation to Related Work in Progress Elsewhere

Knowledge based expert systems (KBES) are a relatively young discipline in the construction field and, at this writing, are still in the early stages of development.

Work on expert systems is underway at the Construction Engineering Research Laboratory (CERL) in collaboration with the Universities of Colorado and Illinois. These efforts are directed toward an expert system which attempts to determine whether a contractor has a valid claim under the differing site conditions clause of a federal contract.

Additional work is being done on an expert system for analysis of a construction network schedule.

Similar work is in progress at Carnegie-Mellon University on an expert system for construction project planning. Here, the focus is to accumulate expert knowledge for the purpose of developing a construction schedule (8,22,31,32).

In the objectives section of this proposal, we endeavored to delineate between the planning and execution of field operations. In our judgement, the work at Carnegie-Mellon is at the planning level and our proposal is at the execution level.

Research at MIT in expert systems in construction include an expert system for data base management to organize 15,000 separate projects each of which contains about 400 items. Another current project for preliminary design aims at cloning the rules and procedures of a cafeteria design expert so that a preliminary cafeteria layout can, in his absence, be drawn to any particular site.

Although not in the category of expert systems, related work at the execution level is being done at Stanford University on automated real-time data acquisition and monitoring. At the University of Maryland, the University of Michigan, and at Penn State work continues on the CYCLONE method of simulating construction processes (2,3,13,15,26,30,42,43).

It is expected that our proposed research will complement this work at the execution level by providing additional knowledge from the perspective of the project superintendent.

G. General Plan of Work

Development of the proposed knowledge based expert system for construction field operations will be divided into the following major phases:

1) **Selection of Participants**

   An early task during this phase will be the identification and selection of domain experts. We will first look at recently retired superintendents in the Atlanta area who could participate on an as-needed basis. These candidates will be thoroughly screened and interviewed to establish their qualification as an expert in the domain of interest to this research. A modest honorarium will be offered to formalize the expert's commitment to the project.

   We intend to supplement our knowledge gathering efforts by using currently active field superintendents. We are confident our contacts in the local construction community will permit the use of these individuals on a part-time basis. Ideally, we would select a superintendent who is between projects or who is in a phase of a project where his duties would permit limited participation.

2) **Problem Identification**

Once the expert has been identified and brought on board, we will begin to define and characterize the supporting knowledge structures. Here we will examine what data is available, what are the important terms and relationships, and how is relevant knowledge to be isolated and verbalized.

We will begin our first formulation of what a solution should look like and what concepts are used in the solution.

Also, in this preliminary phase, a thorough search of the literature will be made to determine what existing algorithms and data bases might contribute to the knowledge base.

3) **Conceptualization**

In this phase, we will articulate more precisely the key concepts and relationships for the knowledge base. The domain expert will continue to be closely involved in the process. We will begin looking for patterns and strategies. Justification of strategies will play an important part of this phase.

Most of the knowledge will be derived from interviews with the expert. Among the techniques to be used would include the following:

a) Postulate several representative problems to discuss informally with the expert. Researchers will be examining how the expert organizes knowledge, how he represents concepts, and how he handles uncertain or imprecise knowledge.

b) Have the expert describe a typical problem for each main category of answer established to date.

c) Ask the expert to solve a series of problems and explain his reasoning as he goes along.

d) Have the expert pose problems to solve using rules acquired from interviews.

A tentative structure should begin to emerge for one or more basic concepts. Although these basic concepts represent only a small portion of the experts knowledge, it will be beneficial to carry them to the next phases in an effort to develop a small prototype system. Since knowledge gathering is an iterative process, we will return to this phase many times

4) **Formalization**

This phase will involve mapping the concepts and relationships identified above into an inference network and developing preliminary IF-THEN rules.

At this point, the researchers should begin to establish any causality between concepts and begin to understand the nature of the data available.

Also at this point, the researchers will make preliminary assessments on how to deal with any uncertainty in the relationships. That is, whether certainty factors, fuzzy sets, or Bayesian probability might be appropriate.

Finally, the researchers should be able to confirm their initial selection of rule based representation of the knowledge base.

5) **Implementation**

In this phase, we will develop the first working prototype. Our goal here will be to eliminate to the extent possible any inconsistencies in relationships and prepare a working program for testing.

The rules will be entered into the knowledge base of the tool chosen to run the prototype. Any required user interface will be included.

6) **Testing and Validation**

In this phase, we will evaluate the prototype system. At the end of this phase the program should run from start to finish on several example problems.

The researchers will be looking to see that the system makes decisions the expert would agree with, that the inference rules are consistent, that the control strategy considers items in the natural order, that the system's explanations are adequate, and that the conclusions reached are properly organized and presented in the right level of detail.

During this phase, we would have the expert critique the prototype's rules and control structure. We would also bring other field superintendents in and let them use the system. It would not be unexpected for conflicting opinions and expertise to surface at this point. These conflicts would need to be reconciled or included as alternative strategies.

7) **Expansion of the Knowledge Base**

Once the prototype works satisfactorily, the researchers will expand the knowledge base in depth and breadth. In this effort, we expect to iterate steps one through five above in much the same manner as the development of the prototype.

8) **Publication of Results**

Results of the research will be reported in technical and professional papers throughout the research period. A comprehensive final report will be prepared at project completion.

9) **Exploration for Future Research**

Preliminary exploration for future research will be conducted toward the end of the project.

H. Project Organization

Investigators

The co-principal investigators are Dr. R. Kangari and Dr. L. S. Riggs. The research team will be organized into two subgroups: a knowledge-based expert system modeling group and a knowledge acquisition and construction operation design group as shown in Figure 2.

The proposed research requires the efforts of a multidisciplinary research team with expertise in construction, civil, and artificial intelligence fields. Interaction of these disciplines is a necessary element of the proposed research in order to promote the transfer of technology.

The expert system modeling group will be under the direction of Professor Kangari and will include a Ph.D. graduate research assistant and a project consultant.

Professor Kangari has been an active researcher in robotics and application of knowledge-based expert systems in construction engineering and management. He is a member of the Georgia Tech Computer Integrated Manufacturing Systems (CIMS), a multidisciplinary group in robotics, computer-aided design, automation, and computer-aided manufacturing. Professor Kangari has taught courses in Robotics and expert systems applied to Civil Engineering. Preliminary work in the area of the proposed research has already been undertaken by several graduate students in the construction management program. Professor Kangari is currently working in the completion of a NSF funded research project in the area of robotics.

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

FINAL PROJECT REPORT
NSF FORM 98A

PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING

PART I—PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. NSF Program	3. NSF Award Number
School of Civil Engineering Georgia Institute of Technology Atlanta, GA 30332	Structures and Build. System	CEE-8319498(E 20-603)
	4. Award Period From 9/1/84 To 2/28/87	5. Cumulative Award Amount 144,654

6. Project Title

" Robotics Feasibility in the Construction Industry "

PART II—SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

The main objective of this research was to develop a methodology to evaluate the potential of given construction processes and work tasks for robotization. The research was divided to five major tasks: 1) identification of high return operations, 2) analysis of standard technologies in selected operational areas, 3) extension of existing studies using videotype analysis, 4) study of existing and projected capabilities of robots, 5) microanalysis of motions associated with construction work tasks, and 6) evaluation of high return work tasks. During the first year of this research workshops with professionals were conducted to discuss potential construction operations for robotization and identify candidate processes for robotization. These workshops were held at Georgia Tech and summary information regarding three workshops is given in the NSF annual report. The purpose of convening these workshops was to discuss the concepts of automation and robotization with practitioners in the field and get feedback from industry concerning possible areas for automation. On going work was directed towards modeling and analysis of standard technologies using CYCLONE simulation techniques. The objective of this work was to study standard work sequences at the micro task level (i.e., work activities with duration of minutes or hours). An evaluation technique based on expert system was developed. The results of workshops on robotics was translated to production rules in order to establish an expert knowledge base. The final result of this model is a set of recommendations about a given construction process which describes whether it should be robotized. During the first phase of research seven technical papers published, three conference papers were presented, and two new graduate courses (Robotics in Construction Industry, and Expert Systems in Construction) were developed. Work to be accomplished in the coming (last) year of the grant will be consistent with activities described in the original schedule.

PART III—TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

1. ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM: Check (√)	TO BE FURNISHED SEPARATELY TO PROGRAM: Approx. Date
a. Abstracts of Theses	✓				
b. Publication Citations		✓			
c. Data on Scientific Collaborators		✓			
d. Information on Inventions	✓				
e. Technical Description of Project and Results		✓			
f. Other *(specify)*					

2. Principal Investigator/Project Director Name *(Typed)*	3. Principal Investigator/Project Director Signature	4. Date
D. Halpin & R. Kangari/ G. Albright		3-2-86

NSF Form 98A (3-83) Supersedes All Previous Editions

Form Approved OMB No. 3145-0058

28 October 1985

Subject: Interim Progress Report

To: Gifford Albright

Division of Engineering Science

in Mech., Structures, and Materials Engineering

National Science Foundation

1. Name of Institution: Georgia Institute of Technology

2. Names of Principal Investigators: Daniel W. Halpin and Roozbeh Kangari

3. Grant No. CEE-8319498

4. Starting Date: 1 Setember 1984

5. Completion Date (Anticipated): 31 December 1986

6. Grant Title: Robotics Feasibility in the Construction Industry

7. Summary of Progress to Date:

A summary of progress based on the major items in the original proposal schedule is given in the sub-paragraphs below. In effect, all items scheduled for work during the first year have been commenced and satisfactory progress has been achieved.

7.1 Identification of High Return Operations

Workshops with professionals were conducted to discuss potential construction operations for robotization and identify candidate processes for robotization. These workshops were held at Georgia Tech and summary information regarding thee workshops is given in Appendix B. The purpose of convening these workshops was to discuss the concepts of automation and robotization with practitioners in the field and get feedback from industry concerning possible areas for automation.

The following classifications were used for characterization of candidate operations for automation and/or robotization:

(1) Dangerous, hazardous, and brainkilling operations

(2) Operations requiring a high level of precision

(3) Operations with high potential for production improvement

(4) Operations with potential for cost improvement

(5) Operations which utilize craft expertise which is vanishing

(6) Operations with a high potential for restructuring and innovation

Details regarding this preliminary survey of candidate operations are given in Reference 3, Appendix A.

Special attention was given to the identificaton of hazardous construction work tasks. Mr. Mendoza, a graduate research student, conducted a study to identify the major hazardous operations suitable for robotization. As part of this study, he developed an evaluation technique for establishing the level of hazard based on OSHA requirements and permissible exposure limits. Details of this study are presented in Reference 4, Appendix A.

7.2 Analysis of Standard Technologies

On going work is directed towards modeling and analysis of standard technologies using CYCLONE simulation techniques. The objective of this work is to study standard work sequences at the micro task level (i.e., work activities with duration of minutes or hours). Preliminary study of the concrete finishing process is contained in Ref. 3. This operation was selected since it is repetitive, requires precision, and can be boring. It has been robotized by several Japanese firms and this study will hopefully help identify what attracted researchers in Japan to develop prototypical equipment to handle this process. Several other operations to include rebar fabrication and rebar placement will be studies during Fall 1985. Tunneling and mining operations have been automated to a high degree and will also be modeled. Operations such as grinding, sand blasting, and bush hammering, as well as pavement breaking and similar demolition activities are being considered for study.

7.3 Extension of Existing Studies Using Video-Tape

Video tape studies have been made of several processes and evaluation of the work sequences involved is in progress. Processes which have been video-taped for the purpose of study include:

(1) Rock Quarrying

(2) Concrete block laying

(3) Steel Member Fabrication

(4) Steel Member Fabrication

(5) Pile Driving

(6) Pour in Place Concrete Barrier Wall Construction

(7) Reinforced Earth Retaining Wall Construction

Reduction of these processes to work task sequences for the purpose of identifying tasks with a high potential for automation/robotization is being accomplished.

7.4 Microanalysis of Motions

Functions of robot control vary according to the complexity of the work task involved in the process. A complex work task is viewed by the robot control as group of primitive tasks which need to be processed in order to finish the complex task. Figure 1 shows the relationship between these primitives and the corresponding level of robot sensory control.

The motions to be performed by a robot constitute a complex work task. High level vision sensors reduce complex tasks to a set of simple ones. These in turn are further broken down into elemental moves by intermediate vision processing. Elemental moves are the movements required by the different parts of the robot to process a given task.

These elemental moves are at a level subordinate to the work task as defined in Halpin and Woodhead (Reference 8, App. A) Methods-time measurement (MTM) concepts are being used to analyze these motions for high potential work tasks with high automation potential.

7.5 Development of Evaluation Technique for Ranking High Potential Work Tasks

An evaluation technique based on expert system will be developed. Preliminary study of various expert systems has already started. Utilization of microcomputer expert programs such as Insight Knowledge Systems Vers. 1 and 2 from Level Five Research, and the Deciding Factor, as well as other programs on mainframe (LISP) has been investigated.

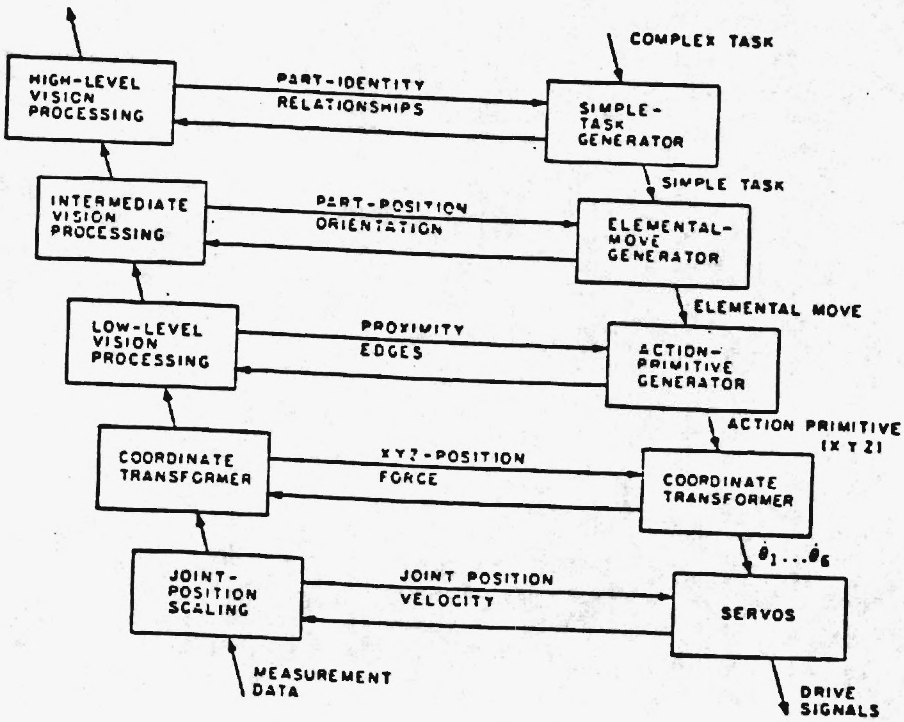

Figure 1. Relationship Between Primitive and Robot Control

The evaluation techniques based on these programs will combine the expertise of the parties involved in construction industry. The results of workshops on robotics will be translated to production rules in order to establish an expert knowledge base. Then, the results will be combined with an algorithmic model which estimates cost, profit return, and production of the operation. Utility value analysis will be considered whenever sufficient information is not available.

The final result of this model will be a set of recommendations about a given construction process which describes whether it should be robotized. A confidence level will be associated with each outcome. Necessary suggestions to improve or further automate a construction process will be provided. The methodology is designed to quantify qualitative judgements on the part of an expert group, and to combine that with the results of algorithmic model which estimates cost and production.

8. Current Problems and Favorable Developments

Work on this project will be impacted by the fact that the senior principal investigator has accepted the A.J. Clark Chair Professorship at the University of Maryland. This will result in coordination problems. It is recommended that the second year funding be moved to the University of Maryland. The attached second year budget has been modified to reflect moving the grant to Maryland. The amount of $64,654 will be expended at Georgia Tech. The remaining amount of $80,000 will be expended at Maryland.

9. Summary of Work to be Accomplished in the Subsequent Budget Period

Work to be accomplished in the coming (last) year of the grant will be consistent with activities described in the original schedule.

10. Other Pertinent Information

The revised budget with funding through the University of Maryland is given in Appendix D. All first year funds will be obligated by Georgia Tech prior to 31 December 1985. It is requested that second year funds be made available at Maryland on or before 1 December 1985. Figure 2 shows the research schedule.

Figure 2. Research Schedule

ACTIVITY	1984 S|O|N|D	1985 J|F|M|A|M|J|J|A|S|O|N|D	1986 J|F|M|A|M|J|J|A|S|O|N|D	1987 J|F|M
1) Literature and Background	XXXXXXX			
2 Identification of High Potential Construction Operations	XXXXX	XXXXXX		
3) Analysis of Standard Technologies (CYCLONE Modeling)		XXXXXXXXXXXXXXXXXXXXXX	XXXXXXXXXXXXXXXXXXX	
4) Extension of Existing Studies Using Video Tape Studies (Time Lapse, Motion Studies)		XXXXXXXXX		
5) Study of Existing and Projected Capabilities of Robots	XXX	XXXXXXXXXXXXXXXXXX		
6) Microanalysis of Motion Associated with Construction Task		XXXXXXXXXXXXXXX	XXXXX	
7) Development of an Expert Evaluation System Ranking High Potential Worktasks		XXXX	XXXXXXXXXXXXXXXXXXXXXX	
8) Publications and Conference Papers		XXXXXXXXXXXXXXXXXXXXXX	XXXXXXXXXXXXXXXXXXXXXX	
9) Quarterly Technical Reports	X	X X	X X X	
10) Annual Report		XX		
11) Preparation of Final Technical Report				XXXXX

Appendix A

Publications and Conference Presentations

TECHNICAL PUBLICATIONS:

1) "Robotics Feasibility in the Construction Industry," Proceedings of the 2nd Conference on Robotics in Construction at Carnegie-Mellon University, June 1985.

2) "Expert Construction Process Operation Systems and Robotics," Technical Report, School of Civil Engineering, Georgia Institute of Technology, Atlanta, GA, March 1985.

3) "Robotization and Automation in Construction," Technical Report, School of Engineering, Georgia Institute of Technology, Atlanta, GA April 1985.

4) "General Application of Automated/Robotics to Hazardous Construction Work Tasks," M.S. Special Research Problem by E.J. Mendoza, School of Civil Engineering, Georgia Institute of Technology, Atlanta, GA, March 1985.

5) "Automated Sensing for Control and Guidance in Construction," Technical Report, School of Civil Engineering, Georgia Institute of Technology, Atlanta, GA, July 1985.

6) "Modeling Construction Robot Control," Technical Report, School of Civil Engineering, Georgia Institute of Technology, Atlanta, GA, July 1985.

7) "Robotics in the Construction Industry: Union Perspective," M.S. Special Problem by C.J. Obetts, School of Civil Engineering, Georgia Institute of Technology, Atlanta, GA, August 1985.

Other References

8) Halpin, D.W. and Woodhead, R.W., Design of Construction and Process Operations, John Wiley and Sons, Inc., Publishers, New York, 1976.

Conference Papers

1) "Robotics Feasibility in the Construction Industry", presented at the Robotics in Construction Conference at Carnegie-Mellon University on June 25, 1985.

2) "Results of Research on Robotics," presented and discussed at Group #4 (Robotics) Workshop supported by NSF for the development of new research direction at University of Illinois on May 1985.

3) Conference Presentation, "Robotics Applications in Construction," International Workshop on Automation of Mining Devices, Paris, France, May 21-22, 1985.

Appendix B

Summary Information

regarding Workshops

WORKSHOP ON ROBOTICS IN CONSTRUCTION

March 6, 1985

PARTICIPANTS:

- Peter Hickey, CM Rosser White
- Frank Speaks, CM HCB-Construction Comp.
- L. S. Riggs, Holder Construction Co.

- Prof. D. Halpin
- Leonard Bernold, Graduate Research Assistant
- Simon Abou-Rizk, GRA
- Noel Epelboim, GRA
- Sandeep Chawla, GRA
- Fady, Nakad, GRA

Repetitive construction processes or work tasks which:

1) are dangerous, hazardous, unpleasant, brainkilling
   - Precast panels, brick placement
   - Rubbing walls
   - Ditching
   - Stacking elevators
   - Tunneling
   - Sand Blasting
   - Grounding a floor slab
   - Insulation
   - Grinding
   - Chipping of concrete
   - Exterior curtain walls
   - Formwork
   - Exterior scaffolding
   - Panelization
   - Fire proofing
   - Structural work
   - Concrete work
   - Sand blasting
   - Bush hammering
   - Dry walls
   - Sewer maintenance
   - Insulation work

2) need high precision
   - Welding of conections (beam-column)
   - Brick work
   - Post tensioning
   - Form work

3) are critical for improving productivity
   - Delivery of materials
   - Concrete pouring
   - Rebar placement
   - Rebar fabrication
   - Steel decking
   - Stud decking

- Piping
- Concrete finishing (automated towering)
- Full penetration welds (beams)
- Fabrication of conducts (electric)
- Sprinkler pipes
- Plumbing
  Sanitary
  Sewerage
- Wall covering - painting
- Steel cages (slurry walls)
- Cladding fabrication
- Wire mesh
- Tiling

4) are not cost effective
- Drill piers
- Earth work
  Rock excavation
  Cut and Fill
- Cassion
- Brick building
- Curtain walls

5) require vanishing craftsmanship
- Tower crane operators
- Tiling
- Woodwork (doors etc.)

Potential areas for innovation

1) Product Innovation
- Precast panels
- Connections
- Brick laying (panelizing)
- Self leveling forms
- Preassembled window system into panels
- Super glue
- Softer concrete
- Formwork

2) Process Innovation
- Pile driving
- Combinaton of processes
- Exterior concrete insulation (sandwich)
- Deep foundation
- Cassion

3) Material Innovation
- Fiber concrete
- Plank construction
- Precast parking deck

WORKSHOP ON ROBOTICS IN CONSTRUCTION
APRIL 9, 1985

PARTICIPANTS:
Greg Bobbs, Superintendent in Building Construction
Grant Crate, CM Bellamy Brothers Inc.

Leonard Bernold, Research Assistant
Sandeep Chawla, Research Assistant
Noel Epelboim, Research Assistant
Harmon Jones, Research Assistant
Fady Nakad, Research Assistant

Repetitive construction processes or work tasks which:

1) are dangerous, hazardous, unpleasant, brainkilling.
   - pile driving
     Cable failure, pile falling, noise, dirty
   - caissons
     cave-ins, gases
   - coffer dams
     pressures, underwater control
   - demolition
     dust, noise, asbestos or disagreeable material
   - sewer lines
     cave-ins
   - painting (high girders)
   - welding (high rise steel)
   - post-tensioning
   - cleaning steel girders (in place)
   - shingling
   - bolted splices
   - decking
   - tying reinforcing
   - underwater work

2) need high precision.
   - sewer lines
   - curvature of curbs
   - segmental bridges
     automate processes at the casting yard
       i) self cleaning forms
       ii) movement of forming beds
   - panelizer
   - floor plan layout
   - reinforced earth
   - reinforced steel
   - bridge riding surface
     concrete finishing machine, power bull float
   - saw cutting

3) are critical for improving productivity.
   - tar roofing
   - material handling

eliminate double handling in small areas
- superstructure decking

4) require vanishing craftmanship
   - concrete finishers
   - carpenters
   - plastering

Potential areas for innovation:

1) Sensors - to monitor wear and tear on a piece of equipment to avoid hazards (e.g. crane cables and brakes), preventative maintenance (e.g. lubrication)

2) Monitors - where the operator cannot see what is going on

3) Controls - push buttons, voice actuated

4) Automatic leveling for fork lifts

5) Sonar on concrete screen to check minimum cover on embedded steel

6) Wind compensator for cranes

7) Tools
   - automated hammer to follow a chalk line
   - saw with automatic device for control, distance measurement
   - coring machine
   - automatic feed for welding rods
   - underwater work (remote control, video cameras, cutting tools)

WORKSHOPS ON ROBOTICS IN CONSTRUCTION
April 23, 1985

PARTICIPANTS:
Bob Angelo, V.P. Matterhorn Industries, Ltd.
P. Cabell Gregory, President American Equipment Co., Inc.
Jim Woods, Board Chairman Matterhorn Industries, Ltd.

Leonard Bernold, Research Assistant
Harmon Jones, Research Assistant
Fady Nakad, Research Assistant

Repetitive construction processes or work tasks which:

1) are dangerous, hazaadous, unpleasant, brainkilling.
- Underground piping, ditching
- Repetitive lifting by cranes
  operator boredom, human error, not thinking
- Antiquated equipment (steel industry)
  blast furnaces
- Material handling throughout all fabrication activities
- Tower crane operation
  operator may not be able to see the end of the line
- temporary riggings in steel erection
- welding
- steel fabrication
  fitters

2) Need high precision
- layout
  anchor bolt, site plan
- plumb the building
- hand/eye coordination of heavy equipment operation
- fine grading, grade contouring
- drop (cutting waste) minimization
- measuring pieces in fabrication

3) are critical for improving productivity
- material handling
- painting
- siding insulation
- scaffolding
- welding decking sheets

4) require vanishing craftmanship
- steel fabrication
  dirty work, skilled people find a better jobs
- carpenters
- insulation
- fitters
  template fabrication for ductwork
  operators

Potential areas for innovation:

1) Equipment
   i) sensor to determine weight of crane load
   ii) control of crane boom angle under loading

2) Products
   i) inflatable forms
   ii) plastic fiber for concrete reinformcement
   iii) bonding materials, adhesives

3) Material
   i) new types of concrete
   ii) new rustproofing treatment of steel

Appendix C

Abstracts of Technical Reports

And Graduate Course Development

Robotics Feasibility in the Construction Industry

ABSTRACT

Many industries as construction are just beginning to realize the impact of full automation in their productivity, quality improvements, and safety. At the present time, robotics in construction industry are still on the stage of basic research. Major motivations for the application of robots in the construction industry are to increas productivity, improve worksite safety, enhance construction quality, and to perform superhuman tasks. The main objective of this paper is to explore the socio-economic aspects of the robotics feasibility in construction industry, and establish a basic foundation for future research. In general, the following questions will be addressed. What are the economic benefits of robotics? What are the impacts on labor? How can construction operations with high potentials for robotization be identified? Seven major variables affecting the feasibility of the robotics in construction industry are identified as: 1) cost effectiveness; 2) level of hazardous; 3) productivity; 4) quality improvement; 5) standardization of design and level of repetitiveness; 6) union resistance; and 7) technologically feasible. Each of the above areas are explored. To models are presented for the robotics feasibility in the construction industry: 1) simplified management decision model; and 2) utility decision model. The ultimate output of these models provide an index which indicates the level of automation.

General Application of Automation/Robotics to Hazardous Construction Work Tasks

ABSTRACT

This report provides information on the hazardous conditions that appear in certain construction work tasks, and presents an evaluation method for the hazardous conditions. A classification of hazardous construction operations is presented using data from the OSHA. The report provides different kinds of work task diagrams that can help the contractor into making an evaluation of these work tasks to consider robots. The approach taken to establish this rationale is first to introduce a series of diagrams that will show a "step-by-step" procedure for accomplishing each work task. Second, it will indicate where and how a hazardous condition can occur and how it can be measured, using the special instruments and evaluation criteria. With these sources of information, the safety professional can analyze the work conditions that are present at a job site. If the work conditions are hazardous to the workers, he can replace them with a robot or an automated remote control machine, otherwise, if there is no hazard involved, the work task can be finished without any interruption.

Expert Construction Process Operation Systems and Robotics

ABSTRACT

A methodology for building expert construction operation design system for the automation and robotization of construction processes are presented. The model allow the engineers to design a construction process operation as if the most construction field expert was providing advice and guidance based on long experience. The proposed expert design system can also serve as training and teaching tools, providing the students a synthetic experience in dealing with design of ill-defined cyclic construction operations which are suitable for robotization.

During the next decade, the field of expert systems will have an impact on all areas of construction field where knowledge provides the power for solving construction engineering and management problems. The first and most obvious will be the development of construction knowledge base which converts the professional construction knowledge into an efficient and productive industrial field. The second benefit is that the expert construction systems will catalyze a global effort to collect, codify, exchange, and exploit applicable forms of construction engineering and management knowledge. The third benefit is that the basic capabilities of the developed expert design model can be extended to provide interfaces to the sensors and consequently the development of real robots in construction industry.

Robotization and Automation in Construction

ABSTRACT

This report addresses the problem of mobility of robots and the limitations in general, develops a selection criteria for identifying potential construction processes, and describes a concrete finishing process as an example for modeling and analysis using CYCLONE techniques. Various mobility systems and navigations such as: 1) remote controlled vehicles (RCV); 2) servo-controlled vehicles (SC); 3) autonomous computer controlled vehicles (CCV); and 4) semi-autonomous computer controlled vehicles (SCCV) are presented. The following major factors were considered: environmental protection, position dtermination; path determination; machine-machine communication; man-machine communication; dynamic control and steering architecture. A selection criteria for identifying potential construction processes for robotization and automation is developed. The model considers the following major factors: hazard, repetitiveness; quality; productivity; and mobility. This report also summarizes the results of workshops on robotics in construction held at Georgia Tech. The workshops identified the high potential construction operations which are suitable for robotization. The potential areas for innovation are discussed and explored.

Modeling Construction Robot Control

ABSTRACT

CYCLONE technique is used to model construction processes for robotization and automation. The report describes how modeling can be used to study robot control. Robot control represents a complex system and therefore requires a multi level or hierarchical approach to study its structure. Systems theory and cybernetics offer excellent tools to study dynamic systems. Modeling the robot control on the other hand allows to abstract from a physical system but still depending on a full understanding of what is really happening. A robot represents a self correcting system which is able to handle inconsistencies in its environment. It performs the desired task based upon the input data which is fed into it. The control unit processes the information about the work task and about the rules for performing this task. These rules and work task information is known to the robot prior to the start of the operation. Input conditions and Output results are checked before and after each cycle of process. They are compared in the controller against the knowledge base stored in it. If while matching these results against previously stored knowledge, any variations from the desired track of operation are detected, corresponding instructions are issued to correct that. Process is initialized by the controller in the beginning. Initialization may involve checking the location etc. of the process. Prior to each cycle, the availability of resources e.g. Concrete, Bricks etc. for a given work task is checked. The report also describes the hierarchical levels in construction and senor control systems.

Automated Sensing for Control and Guidance in Construction

ABSTRACT

The instrumentation of human senses are not the only goals of sensor technology. It also tries to take advantage of other physical phenomenon, e.g. magnetism. There are basically two classes of sensors, the status and the analog systems. From a historical point of view, they can be divided into three categories, basic, advanced and most advanced or high-tech sensors. Each category is described and its implementation in construction industry is discussed. Variety of new sensors used by several construction equipment manufacturers, e.g. Komatsu, are presented. The sensors are used not only for monitoring purpose but also t achieve semi-automation, higher accuracy and lower fuel consumption through optimal movement guidance. Sensors for increased safety are presented, human errors and misconduct are causing a large amount of accidents, even on the construction sites. Sensors could assist and monitor human actions and interfere according to predefined schemes. Example for equipment maintenance sensors are presented. Sensors are used for preventive maintenance of equipment by observing crucial machine parts, and operating conditions. Laser tracking systems are used to increase quality in several areas as vertical formworks, or tunnel machine control. The report also discusses the use of sensors for monitoring and updating construction material flow.

Robotics in the Construction Industry:
Union Perspective

ABSTRACT

At this time, the construction labor organizations are nominally interested in the potential use of robotics in the construction industry. This is fostered by the belief that the construction environment is too random and demanding to allow robots to function effectively for the foreseeable future. Thus, no formal policy has been developed towards robotization, and the cavalier statement that "the unions will not stand in the way of progress or the new technology to achieve this progress" can be made easily. However, the labor organizations need look no further than the recent experiences of the automobile and steel industry labor unions to achieve the needed hindsight with regard to what happens to labor when a shortsighted approach is taken toward robotic applications. The old saw - "an ounce of prevention is worth a pound of cure" - can act as a valid red flag which can alert the construction unions to develop guidelines today to accommodate a smooth transit to robotics in the ocnstruction industry and save their union members from future turmoil in their working lives. This report presents the results of interview with middle and upper levels of union management on the subject of robots in construction. The report also proposes a draft guidelines with regard to robotics use in the construction industry.

Robotics and Automated Equipment
in Construction Industry

Course Objectives

The potential for using robotics in the general field of construction is of great interest and concern to several groups. The development of construction robotics in Europe and Japan are far ahead of the United States. Japanese are making extensive use of robotics on the construction site. Even in small countries such as Israel there have been significant developments in the use of robotics in construction. The development of the Robotics in Construction course is not only a concern to graduate students but also practitioners in the private sector, university and other research groups and government officials. This course provides students with the knowledge necessary in the application of robots in construction industry. The second objective is to prepare graduate students for research funded by NSF.

Subtopic Covered

This course covers the following material: classification and definition of robots; mobility system, motor system, vision system, manipulators, economical aspects and justifications, productivity impacts, social aspects, principles of robotics in construction industry, robotics in hazardous construction operations, robotics in underground and underwater operations, and laser control system.

Textbook

The following papers presented at the Conference on Robotics in Construction, at Carnegie-Mellon University, 1984, were used as a textbook:

Paulson, B.C., Automated Control and Robotics for Heavy Construction

Shimomura, Y., Tunneling by Robots

Fenves, S.J., and Rehak, D.R., Role of Expert Systems in Construction Robots

Warszawski, A., Application of Robots to Building Construction

Crowley, J.L., Dynamic World Modeling and Navigation for an Intelligent Mobile Platform

Kano, N., and Tamura, Y., A New Management Tool for Robotized Construction Projects

Manninen, M., Supervisory Control of Large-Scaled Manipulators in Severe Environments

Appendix D

Revised Budget for Second Year

PPENDIX V

SUMMARY PROPOSAL BUDGET At University of Maryland

OMB No. 3145-0058
Exp. Date 12/31/85

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (MONTHS) Proposed	Granted
AWARD NO.		

RGANIZATION
University of Maryland

RINCIPAL INVESTIGATOR/PROJECT DIRECTOR
Daniel W. Halpin

SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	NSF FUNDED PERSON-MOS. CAL.	ACAD	SUMR	FUNDS REQUESTED BY PROPOSER	FUNDS GRANTED BY NSF (IF DIFFERENT)
~~Daniel Halpin~~			2	$ 16,000	$
( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
( ) TOTAL SENIOR PERSONNEL (1-5)					
OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
( ) POST DOCTORAL ASSOCIATES					
( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
(2) GRADUATE STUDENTS				12,500	
( ) UNDERGRADUATE STUDENTS					
( ) SECRETARIAL-CLERICAL					
( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				28,500	
FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				5,985.60	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				34,485.60	
PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000:)					
TOTAL PERMANENT EQUIPMENT					
TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				2,500	
2. FOREIGN					
PARTICIPANT SUPPORT COSTS					
1. STIPENDS $					
2. TRAVEL					
3. SUBSISTENCE					
4. OTHER					
TOTAL PARTICIPANT COSTS					
OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				1,000	
2. PUBLICATION COSTS/PAGE CHARGES				2,000	
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS R. Kangari at Georgia Tech				17,568.36	
6. OTHER				3,000	
TOTAL OTHER DIRECT COSTS				57,553.96	
TOTAL DIRECT COSTS (A THROUGH G)					
INDIRECT COSTS (SPECIFY)					
TOTAL INDIRECT COSTS				22,446.04	
TOTAL DIRECT AND INDIRECT COSTS (H + I)				80,000.00	
RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS GPM 252 AND 253)					
AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 80,000.00 *	$

/PD TYPED NAME & SIGNATURE*	DATE	FOR NSF USE ONLY		
Daniel W. Halpin	11/5/85	INDIRECT COST RATE VERIFICATION		
IST. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date of Rate Sheet	Initials - DGC Program

F Form 1030 (4-83) *Supersedes All Previous Editions*

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPM 233)