CONSTRUCTION ROBOTICS RESEARCH AT PURDUE

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1 SUMMARY

Purdue University research on the application of robotics to construction began in the summer of 1986. It is based on the assumption that construction can benefit from the advanced automation technology available now in manufacturing. The current work activity spans in three directions:

a. Design of a prototype Automated Construction Worker (ACW) for the performance of repetitive surface tasks.

b. Design and evaluation of Flexible Construction Systems.

c. Design of computerized decision aids for robot implementation.

Each of these research areas is presented in some detail.

2 AUTOMATED CONSTRUCTION WORKER

The concept of an Automated Construction Worker (ACW) is being developed. The ACW robot will perform a series of similar building surface treatment tasks, utilizing similar process control strategy, but different, adequate for each task, robot-arm tool effectors. This research aims at identifying and performance of the ACW robot system's intermediate and final integration objectives, as well as the testing and simulation of real construction job site work assignments.

The ACW multi-task robotic system will utilize commercially available hardware components which are standard in current industrial robotic systems. This should eliminate a duplication of effort in the designing and assembling of the hardware, as well as provide us with the system at a lower cost. However, some non-standard, sensor-driven robot control solutions must be designed specifically for this application.

Our experimental system will consist of an Automatically Guided Vehicle (AGV), PUMA 560 manipulator with wrist mounted camera and ultrasonic range sensors. Additionally, there will be stationary camera and ultrasonic sensors located on the AGV to monitor the scene and guide the vehicle through the work environment. Figure 1 illustrates the organization of the ACW robot system:

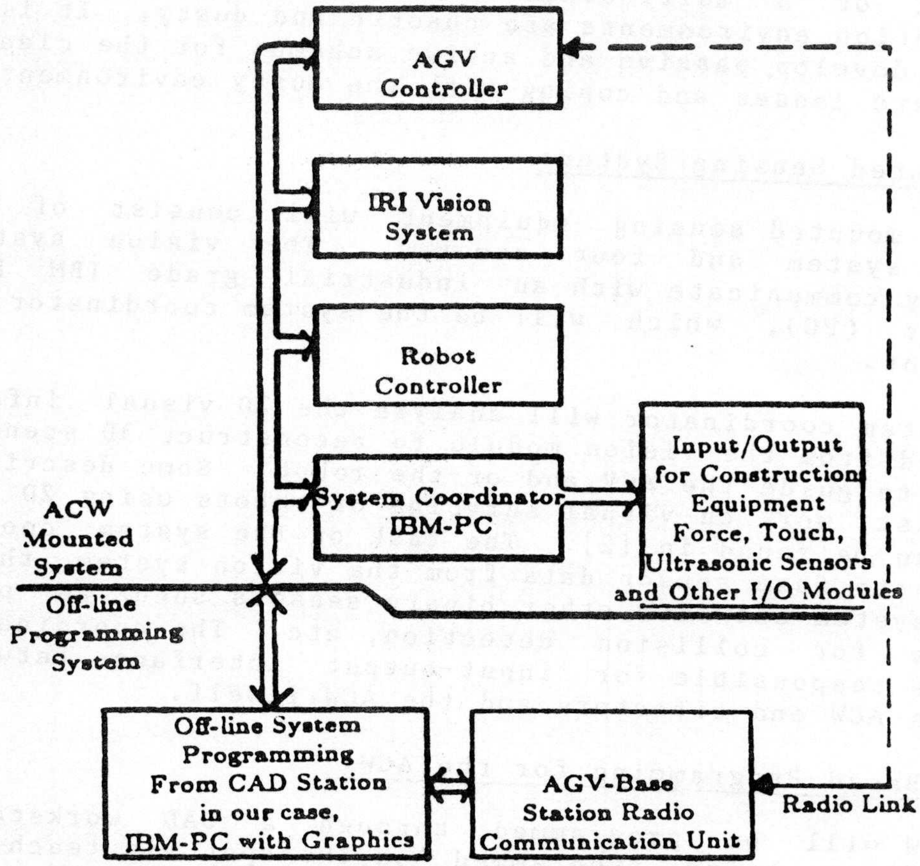

Fig. 1. ACW System Organization

The nature of the construction industry necessitates offline programming methodology, as each building has unique geometry and a program cannot be taught until its construction is complete. In the mass manufacturing situation, the problem is not so constrained as the automation system programming takes place once the design parameters are identified, and when the prototype and the production equipment is set up. Significant savings in manpower can be achieved by such offline programming methods. In the future, the next goal will be to develop a planning system which can automatically generate the work program for the ACW. Details of previous work in the area of offline robot system programming can be found in [1]. One important point which should be noted is that although robots have been applied for paint spraying of automobiles and other industrial equipment, the tasks, in such instances, are very well defined and repetitive. However, in the construction industry the ACW must locate itself using approximate internal models of the building. The location of the ACW will be calculated from sensing features such as walls, corners, ventilation ducts, windows, and the like. Once the ACW is correctly located, then the application of the necessary finishing material or operation may be initiated. This problem of locating the ACW-based internal models and sensing is similar to that of a multi-sensor based industrial robot. Current construction environments are chaotic and dusty. It is necessary to develop passive and active schemes for the cleaning of the camera lenses and coping with the dusty environment.

AGV Mounted Sensing System:

The AGV mounted sensing equipment will consist of an IRI vision system and four cameras. The vision system will directly communicate with an industrial grade IBM Personal Computer (PC), which will be the system coordinator for the ACW robot.

The system coordinator will analyze the 2D visual information obtained from the vision module to reconstruct 3D scene information to guide the AGV and or the robot. Some description of our past work on visual servoing of robots using 2D information can be found in [2]. The task of the system coordinator will be to fuse sensor data from the vision system, the ultrasonic system and from other binary sensors such as proximity sensors for collision detection, etc. The coordinator will also be responsible for input-output interface between the various ACW end effectors and the ACW itself.

Model-Based Programming for the ACW:

The ACW will be programmed through a CAD workstation as opposed to being programmed on the spot via teach/playback schemes. This will enable an architect to create a design database which can be directly utilized by a construction engineer to generate ACW programs control in batch production-like situation [3].

Brief Description of Hardware:

The following commercially available hardware will be utilized in the construction of the ACW system:

- "PUMA 560" Robot: The robot has six degrees of freedom and will have various applicators mounted at the manipulator wrist. The robot is programmed via VALII language [4] utilizing transforms. The system coordinator will issue transforms which the end-effector has to accept.

- "US Robot" AGV: The robot is able to carry up to 250 pounds payload. Current system will tract a reflective tape placed on the ground. The system will be directed from the system coordinator once visual information is gathered. The AGV is programmed via a radio link from a base station.

- "IRI" Vision Module: This is a 2D binary/grey level image processing system. It offers development environment for new algorithms. This will allow to adopt the appropriate image processing and recognition techniques for several different surface applications.

- "Lord" Force Sensor: A wrist force sensor will be mounted on the PUMA robot to sense contact forces. This will allow the manipulator to perform calibration operations by making contact with the building walls, or during refilling operations and end-effector change operations. In such instances force information is essential to verify the completion of a series of contact sequences or compliant motions [5].

- "Lord" Tactile Sensor: The task of the tactile sensor is to verify that the parts in the gripper are in position and their orientation is accurately known. Therefore, the motions of the robot tools can be accurately predicted. This will allow precision operations during calibration and loading/unloading operations.

- Ultrasonic Sensor: Ultransonic sensor will be used to measure approximately distance between the robot and the walls and other obstacles. Information from the ultrasonic sensor and the vision will be used to control the position and orientation of the sealant applicators during the ACW operations.

- System Coordinator: An industrial grade IBM PC with additional single board sensing and input/output controllers will be used to control ACW internal functions as well as for general purpose system programming tasks.

- ACW End Effectors

  o "Vacu-Blast" sandblasting gun: One 11 mm rotating supersonic blast nozzle with a suction device drawing the abrasive, dust, dirt and accumulated foreign matter by pneumatic means.

  o "Educt-o-matic" portable spotting blast gun by Clemco-Clementina with blast head, abrasive container and dust filter.

  o Ancillary equipment (e.g. 19 mm rubber hose, air compressor, pressure vessel connecting hardware, abrasive container).

- o "Spin Jet" Robot Cleaning System by National Liquid Blasting Corp. It is a water jet cleaning manipulator for heavy duty cleaning in industrial applications.
- o Jet Spraying manipulator by Tokico America, Inc. Robotics Division (part of "Armstar," Automated Finishing System for paint application to wall surfaces).
- o "Surclean 153" surface reflectance meter by "Elcometer Instruments" or similar device for the continuous measurement of wall surface cleaning quality. The results of the monitoring process will be recorded by a microprocessor unit and fed back into the robot control system for decision making.

The ACW system is expected to provide a flexible work tool for the automated performance of repetitive surface application tasks. Examples of such tasks include paint spraying, sandblasting and polishing. Significant benefits from the ACW operation can be achieved, including labor savings, improved work quality, and the removal of workers from hazardous environments [6].

3 FLEXIBLE CONSTRUCTION SYSTEMS

A functional model of an industrialized, partially automated building construction site, including its external facilities and relationships is under consideration. The model assumes removal of a number of some highly repetitive work tasks from the immediate construction site, providing for their automated performance at an off-site location. Some of the on-site operations must be redesigned to meet the robot performance procedure requirements.

Our research objective includes the development of a design and evaluation methodology for construction work automation. It will be accomplished by a study of the feasibility of an automated target building construction system. The target system contains a relatively large variety of generic operations and work layout configurations that are commonly applicable to other operations throughout the construction industry. We are investigating the possibility of work task integration into smaller subsystems that can be characterized by sets of analogous work operations. In the long range, this approach can lead to a fundamentally different building design and construction organization system which involves interaction and interdependence of on-site, proximate, and off-site (prefabrication plant) work processes. Construction will then be performed separately by humans or machines, or by humans and machines jointly, and coordinated to benefit from the best features of each.

After the integration of relevant tasks into new automated performance subsystems, a limited number of new configurations will be designed, analyzed and simulated to estimate their physical performance. The design and analysis of the subsystem will be determined according to the nature of tasks, equipment and tasktime required, and the anticipated location of the work process.

A methodology for integrating generic construction processes into a multi-level construction system with work automation capability is presented in Figure 2.

Several estimation measures will be developed for the purpose of estimating performance of the target robotic construction system. One such measure can be defined as the Composite Measure of Complexity (CMC) for an investigated task or process. The CMC will be estimated by means of linear regression and represented in a mathematical function as follows:

$$CMS = F\,(C_M, C_E, C_T, C_D, C_S)$$

where

C_M = construction material and accessory characteristics index (numeric coefficient reflecting material or component purpose dimensions, weight, cost, comparative strength and survivability in adverse conditions)

C_E = variable coefficient reflecting capability and operating cost of traditional or advanced (NC or robotic) equipment used in production of structural component(s)

C_T = time required by machine and/or laborers to perform pre-on-site-erection fabrication

C_D = coefficient reflecting logistic effort necessary to deliver building structural components from the fabrication yard to erection site

C_S = coefficient reflecting type and operating cost of equipment, conditions and time necessary to erect structural component on site

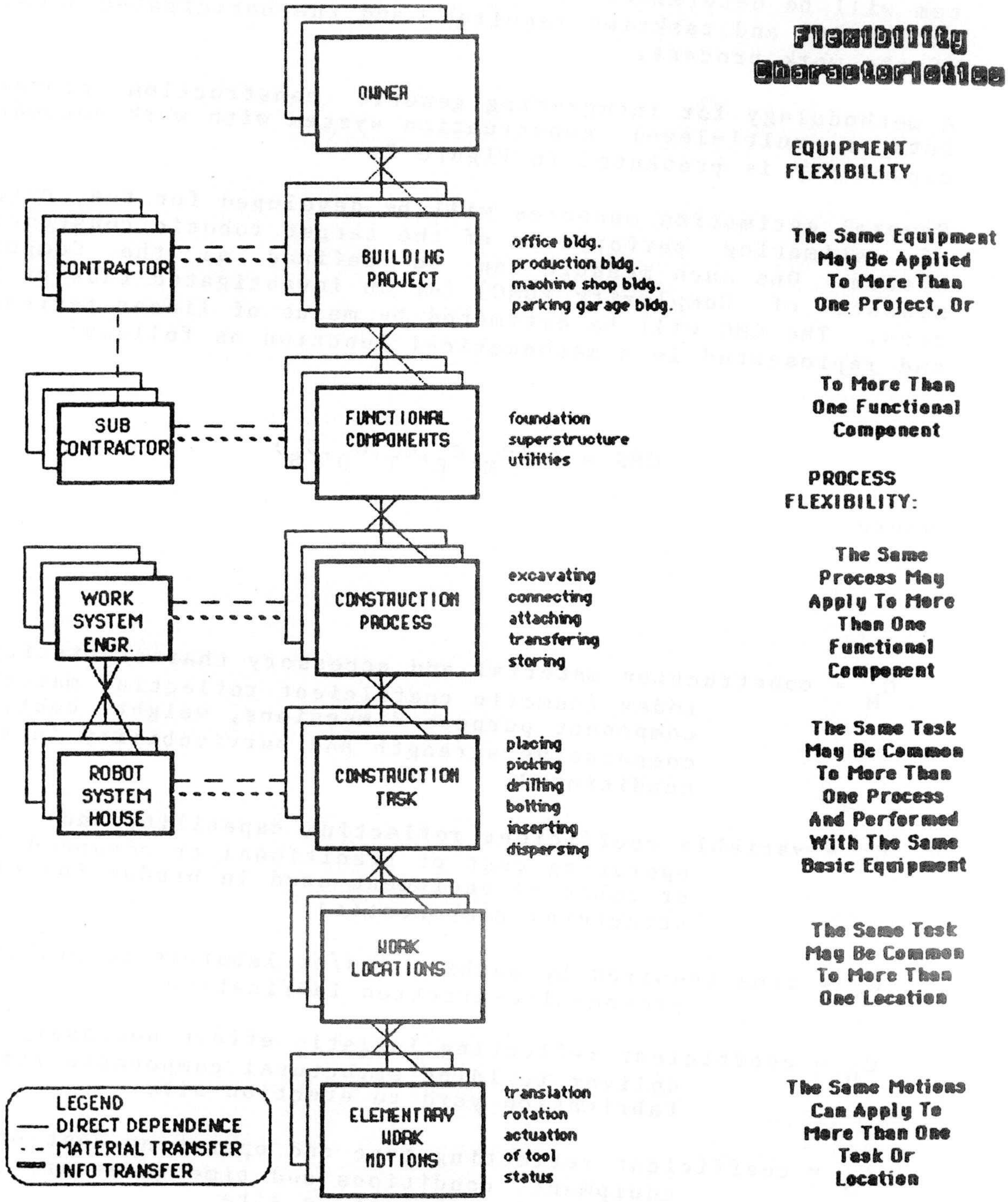

Figure 2. Work Breakdown and Task Integration in a Robotic Building Construction System.)

The functions within the CMCs must be estimated for each construction activity at the `Task´ and `Process´ level (see Figure 2), and used in the performance model of robot-aided construction. The CMC functions should be derived by assessing the level of utility of robotic performance of the examined operation, and feasibility of other affected activities. The necessary information for the estimation of these coefficients can be obtained from the construction organizations and equipment manufacturers and compiled for the use by FCS. The values of CMC will be used to assess the relative level of utility of robotizing groups of tasks composing individual construction processes.

Three major directions of this research will follow:

a. <u>First direction</u>: Ergonomic Data Collection. In this aspect, ergonomic data should be collected on major groups of construction operations typical of the target building system. Consistent systemization of these data into categories according to the operation´s level of automation potential under job site constraints will constitute a basic research effort, first of this kind for the construction industry. Examples of important data collected in this aspect are:

   - Types of buildings produced with systems similar to the target construction system and their current market demands. Information can be obtained from large construction organizations and prefabricated component manufacturers.

   - Typical work tasks within the target construction system and their characteristics. Data can be derived from the analysis of work processes and from contacts with contractor engineers, equipment manufacturers, and from surveys of operators engaged in the relevant work tasks.

   - Time and effort requirements for individual task performance. Data can be obtained through field surveys with cooperating contracting firms and from existing literature (e.g. [7]).

   - Breakdown of the construction tasks into generic operations for automated/robotic performance. This will be accomplished by ergonomic analysis of the analyzed work tasks and by evaluation of relevant industrial work task performance methods.

b. <u>Second direction</u>: Generic Task and New Work Configuration Design. In the second direction, operations in the target construction system will be analyzed for their automation potential. Those with the highest relative advantage from this perspective will be selected. Selection criteria will stem from the following areas:

- Relative task simplicity and repetitiveness, for instance, relatively little requirement for sensory feedback information and process control;

- Ease of removing the operation from and inserting it back into the construction site; ease of placing it at a proximate or off-site location for the purpose of automation;

- Ease of performing the given work process in a factory-like environment (e.g. dimensions and weight of work pieces, accuracy constraints);

- Potential cost effectiveness of the automated work performance (including labor savings, work safety, and improved quality benefits). Cost data can be obtained from large construction firms and analyzed with the methodology developed in previous research by the investigators.

c. Third direction: Analysis of New Task Configurations. In the third aspect, alternative new work configurations will be developed. Facility designs of partially automated construction work systems will be developed and proposed for job site testing. Technical concepts of the automated equipment will be derived from the existing prototypes of construction, nuclear maintenance/inspection and manufacturing solutions (see e.g. [8]), and adjusted for the construction domain performance. The following three main work environment alternatives will be considered:

- On-site construction tasks performed by autonomous robotics and robots working with humans. Data can be obtained from two main sources: (1) from construction equipment and robot system manufacturer's, and (2) from comparative surveys of construction and robotic equipment currently being conducted by the investigators.

- Off-site work tasks in automated facilities (flexible, programmable robotic construction shops involving Flexible Construction System (FCS) concept). Data can be obtained from the existing conceptual designs of automated building prefabrication methods [Warszawski 86] and from industrial robotic layouts in the metalworking and electronics industries [9].

- Transfer tasks that combine on-site and off-site tasks. Research concentrating on logistics and work system design for these tasks will consist of interdisciplinary effort utilizing the experience collected to date by industrial, systems, and construction engineering.

Three performance alternatives with respect to the degree of human input and control over the work task will be considered:

- Human performance of complete task;

- Robotic performance of complete tasks (autonomous and teleoperated);

- Combined robot-human performance of tasks.

Each alternative will be examined for potential performance efficiency and productivity, projected system setup cost, and labor savings. Robot work system models developed in the process of this research will be simulated using software developed for other industrial robot system evaluation [10].

The FCS concept is relatively large in scope and requires the integration of multiple robotics and other equipment into an efficient work system. Practical implementation of this concept depends, among other factors, on the success of robotic construction equipment in the individual work task applications.

4 EXPERT SYSTEM FOR CONSTRUCTION ROBOT DESIGN

Traditional methods of designing the function of construction equipment are insufficient for innovative, automated and robotic equipment to be used on construction sites. The robotics technology for construction applications and new methods of improvement of functional design are vigorously pursued in Japan and should be expected to emerge on U.S. construction sites in the next decade [11]. The following reasons for the lack of adequate functional design tools can be identified:

- All construction robotic equipment is currently available only in the prototype stage or still being designed. Consequently, there is no field performance experience for construction robots to provide feedback regarding their functional and cost efficiency;

- The construction site work environment is ill-structured and constantly changing as the work progresses, thus making it impossible to transfer the available experience of robotics applied in well structured, manufacturing plant environments;

- There is a long lead time for the acquisition and implementation of robotic systems in manufacturing; it is expected that this time will be even longer in construction;

- There are virtually no consulting professionals available for the construction industry who would be knowledgeable of a broad range of issues related to robotics functional design for construction applications.

Expert systems have been receiving initial attention among construction equipment designers. Previous work includes design aspects of construction robot control systems [13]. A significant potential benefit of the expert system containing practical and yet unique system design knowledge in the field of an emerging construction robot application is anticipated.

There is a variety of sources from which different parts of the relevant expertise on individual design and implementation aspects of construction robotics can be obtained. However, at present a majority of robot system designers is unaware of such sources of information or is not capable of collecting the necessary data when faced with a need to make a decision regarding possible technical innovation involving a robot. Almost no consultants or comprehensive consulting services for specific applications to construction projects are available, due to lack of experts in all aspects of application decision making. This has been an important obstacle in the dissemination of knowledge on robot application potential among robot manufacturing firms. Development of a computer expert system containing heuristic knowledge collected and compiled from the proprietors of this unique expertise and subsequently made available to robot designer will alleviate this major difficulty in acquiring the state-of-the-art expertise, and will thus become a breakthrough in the construction application domain.

The research on development of this expert system combines expertise in the design and function of construction equipment, as well as in the design and performance of industrial robotic systems. It is expected that, besides becoming state-of-the-art decision aid to robot system designers, the expert system will enable its designer to acquire a profound understanding of issues and relationships involved in arriving at a correct and successful design of a construction robot.

Several approaches to expert systems development in manufacturing for the design of factory environment in which robots are to work, and for determining functional specifications for industrial robotic equipment exist (e.g. [12]). One approach which is highly relevant to construction work environment was a robot mission oriented method developed for maintenance of nuclear power plants [8]. Similar methodology will be adopted in development of the proposed expert system for the functional design of construction robots. Purpose and function of each robot module will be investigated and compiled in a prestructured data base for subsequent use in expert system development. Lists of design and implementation experts for robots of interests have been compiled by the compilation of data on the existing designs and their field performance.

Expert systems utilize specialized control structure ("inference engine") fed by a rules set ("knowledge representation") to produce educated judgments. The proposed expert system will be designed within a framework of a commercially available expert system "shell." The shell is a domain independent system that allows applications to a designed and developed interactively without the requirement that the designer be proficient in producing computer code. Figure 3 presents a schematic of an expert system design environment.

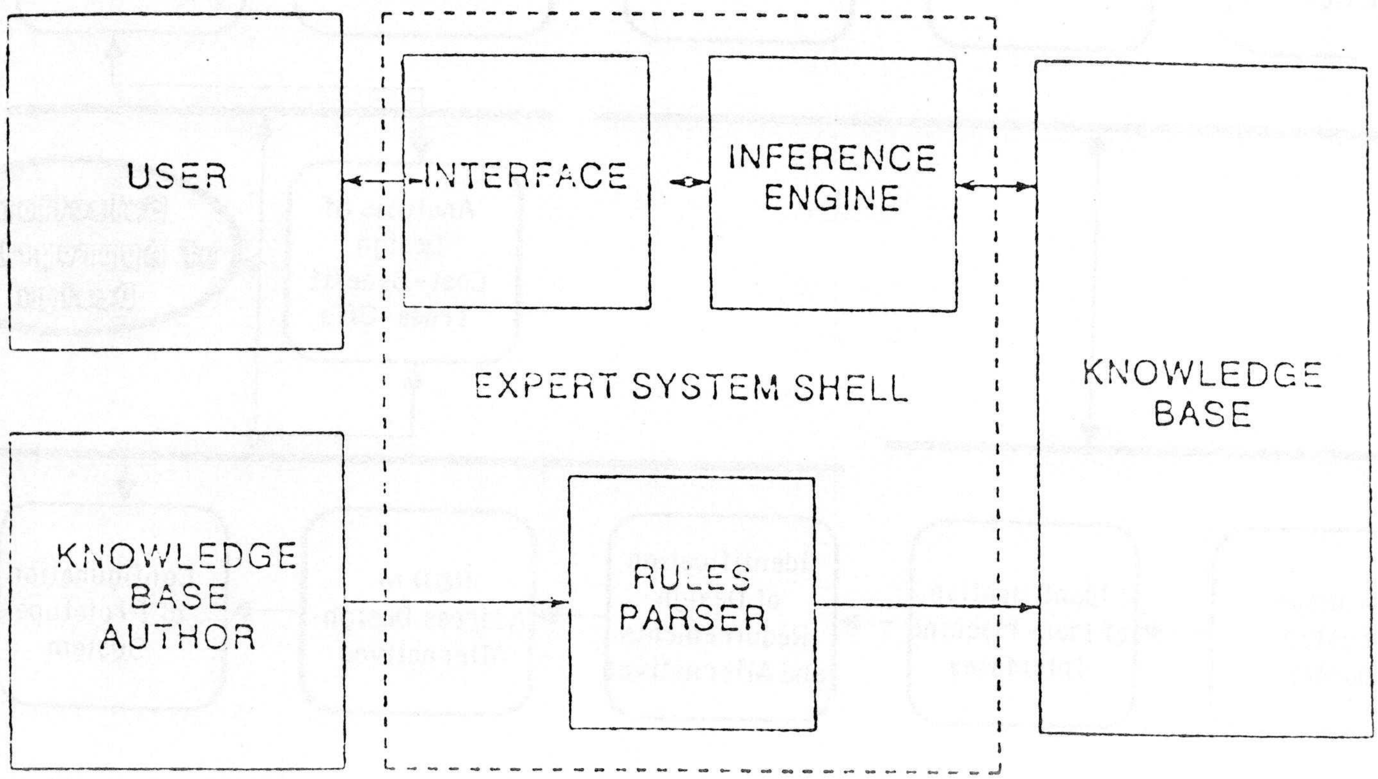

Fig. 3. Schematic of an Expert System Development Environment

The primary role of the shell will be to assist in the creation of a comprehensive knowledge base relevant to the decision steps on robot acquisition and implementation. Consequently, the investigator will be able to spend his time and effort on the actual content of the knowledge base rather than on its structure. This will improve the validity and technical quality of data incorporated in the knowledge base.

A logic diagram of a knowledge base for the design expert system is presented in Figure 4. Similar approach to robot system design without knowledge integration into an expert system was previously suggested for application to nuclear power plant maintenance tasks [8].

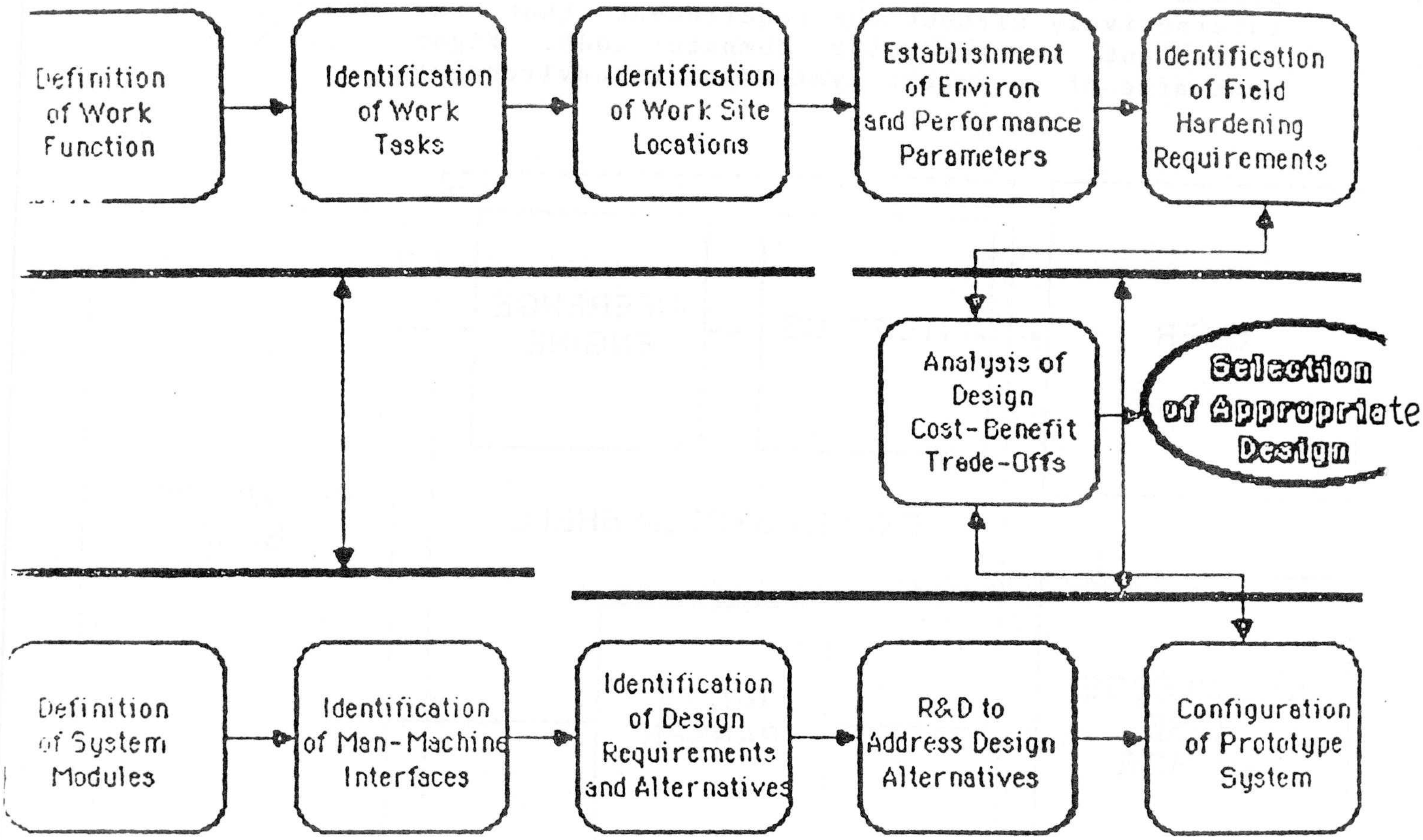

Fig. 4. Knowledge Organization for Robot Design Expert System

The analysis of the existing and other possible designs will produce a set of qualitative and quantitative rules essential in arriving at a robot implementation decision. The rules will be of "if - then" type, which is typical for other existing engineering expert system designs, and must be structured according to their nature and meaning for the robot design algorithm. Weight of implemented heuristics will be assessed by the author-simulated consensus of knowledge sources participating in the creation of the knowledge base.

The system should be designed with knowledge modules grouped in specific domain clusters (i.e. technical, economic, and implementation oriented). The modules will be modifiable and will have potential for expedient updating of current application-related expertise. Also, provisions for a wide range of options for knowledge representation and systems inference engine operation will be made within the implemented expert system shell, including bayesian statistics, literal rule-based production systems, hypothesis testing, and analysis of uncertain information by "fuzzy set" methodology. These options will be used, where practical, according to the nature of knowledge acquired and the desired format of knowledge output.

The following sources of knowledge should be utilized in producing the knowledge base for construction robot design decisions:

a. University researchers: construction technology engineers, robot hardware designers, control system engineers, engineering economists, ergonomists, technology forecasters;

b. Industrial robot manufacturers: hardware specialists, control system designers, system design engineers, cost engineers, marketing professionals;

c. Independent consultants: e.g., robot installation specialists;

d. Robot system users in manufacturing: stationary industrial robotics for paint spraying, coating, polishing, foundry and steel mill applications, automatically guided vehicles (AGVs);

e. Construction robot developers: inspection, testing, reinforcement assembly, surface applications (shotcreting, painting, cleaning, polishing).

The results of implementing such an expert system can significantly contribute to more effective designs of construction robotics by providing a comprehensive feedback to the robct designers. This in turn can lead to a more successful application experience with robots within construction firms, creating potential for rapid expansion of this advanced technology within the construction industry.

5 CONCLUSION

The above three concepts into the working prototypes of construction performance systems will provide a substantial insight into a wide spectrum of robot application issues in this domain. New experience and practical data from these prototype design concepts can be used in planning for future robot implementations.

6 REFERENCES

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