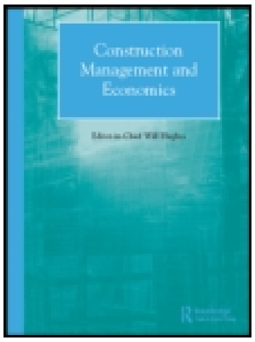

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Identification of factors influencing implementation of construction robotics

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The objective of this paper is to describe major factors influencing the robotization of construction processes, and to provide a model based on fuzzy set theory for feasibility analysis of robots. Major factors influencing implementation of construction robots are described. The primary factors driving the adoption of robotics in construction are identified as: (1) *need-based feasibility,* (2) *technological feasibility, and* (3) *economic feasibility. In order to concentrate on processes which have potential and exclude those processes which are not strong candidates for automation, brainstorming sessions were held with various parties involved in construction to examine feasibility of construction processes for automation. The participants were asked to consider construction processes from the heavy and highway, building and industrial construction areas.*

Keywords: Automation, construction, equipment, excavation, material handling, prefabrication, robot, tunnelling.

Introduction

Most major industries have passed through a period of intense industrialization. Some have reached a period of extensive automation to include the use of robots. In particular, the automotive industry has successfully used robots to enhance both production and improve quality control. Recent advancements in robot technology, control theory, and computers have vastly broadened the applicability of robots. Traditionally, the construction industry has been conservative in accepting new approaches. The industry traditionally has modified existing and proven practice to achieve improvement rather than trying entirely new methods. In recent years, robotics principles have been applied to certain construction operations.

Of the many possible areas for the application of automation in the construction industry, the greatest advancement and utilization to date has occurred in the areas of prefabrication and fixed repetitive work which takes place in a relatively controlled environment. The work is, in effect, brought to the automated machine, where it is processed, and then moved onward to a storage facility, or directly to the construction site. This type of working environment is not far removed from the realm of industrial robotics. Dramatic increases in productivity, reductions in cost, and improved quality control engendered by automation and robotization of industrial processes have been reported in the manufacturing sector.

Another high potential area is automation in tunnelling. The linear nature of subsurface construction lends itself to automation. It would appear that innovations in mining can be transferred to tunnelling operations. Automation of profile guidance and roadway alignment on roadheaders (in mining) has been successful, indicating further possibilities for automation in related areas. With better integrated technology application, it is possible to ensure consistency of operation and reliability over a wide range of tunnelling activities.

Earthwork is an equipment intensive activity and offers an excellent opportunity for the application of automation and robotization. There is an entire class of semi-automatic devices under development or in operation in which computerized functions have been added to normal construction equipment. These include computerized control of blades for graders and bulldozers, computer control for ditch diggers, and computerized control devices for cranes, and computer engine and transmission control of trucks (Paulson, 1985). It appears that excavation is an excellent application area for further use of automation and robotization due to its significance in scale and economic importance. 'It is tolerant of imprecision, well understood as a human-driven process and prototypical of a host of spin-off applications' (Whittaker *et al.*, 1986).

In particular, robotization is beginning to play a role in off-shore ocean floor construction, excavation of gas line installation and crater repair of bomb damaged runways. The Robotic Excavator (REX) developed at the Robotics Institute, Carnegie Mellon University, has integrated sensing, modelling, planning, simulation and operation to unearth buried utility piping (Warszawski 1984). Its objective is to reduce the excavation hazard posed by explosive gases, decrease operation costs, and increase productivity in the gas utility industries.

Another prime candidate for automation and robotization in construction is the material handling function. There are two principal reasons for this. First, material handling is often repetitive in nature, both in actions required and in the nature of the materials which must be handled. Secondly, automation in the material handling function must be achieved, if expanded automation of actual construction operations is to be successful.

A robot may be defined in general terms, as a reprogrammable multifunctional manipulator designed to perform a variety of tasks. In other words, a robot is a mechanism guided by automatic controls. The driving force supporting robotization of a production process is the need and economic feasibility of the robotization. Counterbalancing this need, however, is the technological state of the art, which can either support or present formidable barriers to the automation. Recent progress in the use of robotics in other industrial fields has generated interest in the automation of complicated construction works. Construction robots may be viewed as a potentially powerful way to improve working conditions, to reduce accidents, and to increase construction productivity (Albus, 1986; Ishikawa, 1988; Nakamura *et al.*, 1987; Nakamura *et al.*, 1988; Ueno *et al.*, 1986; and Ueno *et al.*, 1988). Two possibilities for the application of robotic technology can be proposed. The first approach is application of robots in traditional construction sites. In order to achieve this goal, it would be necessary to consider complete reorganization of the construction site to achieve a more structured 'factory' like environment. Job-site reorganization would allow building design and construction planning better suited to robots. A second possibility is to introduce robots into new construction fields such as decommissioning of nuclear power plant and space development.

The objective of this paper is to describe major factors influencing the robotization of construction processes, and to provide a model based on fuzzy set theory for feasibility analysis of robots. To develop this model, feasibility analysis is divided into three major components: *need-based feasibility*, *technological feasibility*, and *economic feasibility*. Each of these areas will be explored in the following sections, and a method for evalulating the overall feasibility will be presented. The goal is to establish a base for systematic identification of potential construction processes which are suitable for automation.

Need-based feasibilty

The objective of need-based feasibility is to determine whether there is a motivation and need to attain higher levels of automation. To identify the characteristics which support the need for robotization, brainstorming sessions were held with a panel of experienced practitioners in design, construction, and research. The goal was identifying specific characteristics of construction processes which would make a particular process a strong candidate for automation or robotization.

The final result of this brainstorming effort was the definition of ten construction process characteristics which support the need for robotization as follows: labour intensiveness, vanishing skills replacement, high skill requirement, precision and dexterity requirement, repetitiveness, tedious and boring, critical to productivity, unpleasant and dirty, hazardous to health, and physically dangerous. The following sections describe these major factors.

Labour intensive processes

Labour intensive jobs are those for which the cost of labour is proportionally higher than materials and equipment costs. Even though automated equipment and tools have replaced manual labour in many construction processes, labour resources are still necessary since the level of equipment technology by itself cannot satisfy the demands of construction (Obetts, 1985). Generally, construction processes are labour dependent because of the expertise, the precision, the uniqueness of the job, or the economic benefits required.

Labour intensive operations in construction, especially those characterized as unsafe, hazardous, uncomfortable, or unpleasant, are suitable candidates for applying automation and robotization technology. Employing robotic devices can provide better production and elimination of congested environments. Among construction processes, concrete placement, carpentry, plumbing piping, and sheet metal work are common labour intensive operations.

Vanishing skills

Even with the training programs sponsored by major organizations and corporations, the construction industry in the US is facing a major crisis in which the available pool of workmen, journeymen, and foremen in many trades is shrinking with no major replacement program underway. This issue has been one of the factors that has moved the Japanese to implement automation and robotization in their construction industry.

Today, the demand for construction is growing. In contrast to this growth, many experienced workmen and foremen are retiring. Even with increased construction pay and benefits, many young people are shifting to white-collar jobs. One problem may be that the industry has not done enough to attract the new generation of potential journeymen.

Precision and dexterity requirements

For all construction operations, precision and dexterity are often the key to work quality. Required precision and dexterity depend on a variety of factors which are related to the process and the environment of the work area. Every work task in a process requires a certain level of precision, however, some work tasks are more critical than others. Processes such as structural welding (Mullins, 1986), and precast cladding are generic examples where precision and dexterity in the connection phase are considered critical.

Repetitive nature

Architects and designers are moving toward implementing the idea of repetitiveness in construction processes to improve cost effectiveness and productivity. Repetition is a beneficial work process attribute since it gives workmen the opportunity to gain a better understanding of their responsibilities as the demand for work is increased. The so-called 'learning curve' effect is permitted to function as repetition increases. Even though many construction operations are repetitive in nature (e.g. bush hammering, ditching, grading, painting, and pile driving), construction processes must typically be modified to incorporate this characteristic.

For automation and robotization, repetitive processes are the key areas where this technology can be implemented. Today, the construction industry has applied automation and robotization techology to some repetitive processes, such as welding and fireproof spraying.

Constuction processes can be classified into three main categories based on the issue of repetition: highly repetitive, semi-repetitive, and non-repetitive. Sand blasting and bricklaying are common examples of the first type. In repetitive processes, resources and durations of work tasks remain relatively unchanged during the construction process. In the second type, processes such as precast structures and rebar placement tend to have changes in resources and/or in duration of work-tasks after resources have cycled in the process for a number of times. However, the structure or the process tends to be relatively unchanged. A common example of the last type is plumbing piping, where the operation of the process generally does not have a repetitive nature. Even in this case, although the whole process is non-repetitive many of the individual tasks making up the process are repetitive, and could be subject to some form of automation.

Tedious and boring processes

Although construction projects are often viewed as being unique in nature, the basic tasks which comprise them are often common to all projects. Since the industry has seen relatively small technological progress, the manner in which these tasks are performed has not changed much over the decades. On the one hand, this is an advantage, because the worker can learn the task with great ease, reaching the peak of the learning curve very quickly, thereby maximizing his productivity earlier during the project's duration. However, since the tasks are the same, and are often repetitive in nature, the construction worker is likely to get bored due to the monotony. Then his attention span lessens, often causing him to overlook details and neglect precision. This problem is futher accentuated when the tasks are tedious in nature, i.e. when they involve monitoring off many fine points and close coordination with other tasks. Effects of work tedium include a decrease in productivity, a decline in the quality of the construction product and often, a deleterious effect on inter-worker relations.

Critical to productivity

Some construction processes have been automated to a certain extent, e.g. earthmoving operations (Whittaker *et al.*, 1986), while certain others are still being carried out manually. It is quite probable that if the mode of operation in the non-automated processes was changed to complete automation, or even a mix of manual and automated methods, the productivity would greatly increase (Paulson, 1985). Construction productivity decline has often been cited as one of the major reasons for the decreasing competitiveness of the US in international construction. If the productivity of the processes could be increased, the productivity of the whole operation would show a corresponding increase. For the purpose of this analysis, the question posed was: 'If the process, as it is done today, is automated, then can its productivity be increased considering the present level of technology?'

Dirty and unpleasant

The construction work place is often dirty and the work tasks are generally unpleasant. Access to the work place is often severely constrained. Present construction practice with its lack of coordinated materials management, often causes the work place to be cluttered with tools and materials. Rarely is there an efficient, regular method for removing the waste material (wood shavings, defective nails and boards, packaging materials).

The construction worker sometimes has to work with heavy, noisy or potentially dangerous tools and has to, in many instances, wear special clothes, footwear and headgear as safety precautions. These can cause difficulty in his movements and actions, and also create physical discomfort, particularly in hot weather. Underground construction, e.g., tunnelling is unpleasant due to constant exposure to dirt and high pressures and few chances of being out in the open air (Barham, 1986).

Hazardous to health

To evaluate construction processes in terms of health hazard, the factors taken into account were: (a) dust, (b) gases, (c) harsh temperatures, (d) level and intensity of exposure to noise, (e) radiation, and (f) pressure. The evaluation technique for establishing the level of hazard based on OSHA requirements, and permissible exposure limits developed by Mendoza (Mendoza, 1985) has been used.

Finishing activities, like bush hammering and sandblasting, are rated high in this category of needs qualification due to the constant exposure of the workers to dust particles. Tunnellers, in contrast, are exposed to gases and toxic fumes underground (Neustadtl, 1986). Certain finishing compounds and chemicals used in construction processes can also decompose into gases when the temperature and pressure conditions change. Frequent exposure to these toxic fumes can cause respiratory diseases and, in certain cases, can affect the nervous system.

Physically dangerous

One of the primary goals of automation/robotization in construction or any other industry is to reduce the level of physical danger to which the worker is exposed. For the purpose of this study, physically dangerous includes all work processes that 'cause death instantaneously, or maim or disfigure workers or cause fatal accidents'.

The hazards in construction include those associated with falls, large masses, and equipment. At present, one obvious area for possible applications of robotics lies in environments like nuclear reactors, toxic and hazardous waste sites and fire fighting. Working on high-rise buildings, especially on their exterior, is phyically dangerous, due to the constant danger of falls. A close second in the category of dangerous tasks are those which involve transporting heavy loads which can fall on the person moving them himself, or on those around, causing severe injuries. Cases of unskilled workers driving heavy equipment are not uncommon on the construction site and there have been cases which have cited such incidents as causes of fatal accidents. The worker insurance rates, published by R. S. Means, give a good indication of the risk levels involved in various trades. For instance, the insurance rates for pile driving crews and structural steel erection crews are much higher than those for tiling crews and workers in the plumbing piping trade (Building Construction Cost Data, 1985).

Technological feasibility

The second step in the overall effort of evaluating feasibility of automation and robotics in construction is technological feasibility within the conditions of the existing and projected state of the art technology in robotics. The technological areas which were recommended to the panel are: material handling requirements, required sensor technology, complexity of required system software, hardware technology, end effector requirements. These areas are described in the following sections.

Material handling requirements

Material handling, *per se*, is technically not an intrinsic or connected part of the essential automation system, as are the other four. However, unless some automated form of material delivery can provide a steady stream of material to be processed, the benefit of a highly automated production process will be negated. The relationship between the speed of processing and the speed of delivery of material is critical to the concept of automation of construction processes. Processes involving no material supply constraints are the strongest candidates for robotization from a material handling point of view.

Material handling is a key factor in automation and robotization of construction processes. Automation in the material handling function must be achieved if expanded automation of actual construction operations is to progress. Material handling entails far more than simply providing a stockpile of material in the immediate vicinity of a robot or moving liquids or semi-liquids with pumps and pipelines. Material handling aspects must be included when considering systems such as site layout, receiving, unloading, inspection, identification, storage control, scheduling, retrieval, movement to the work place, and installation.

Although, the state-of-the-art of material handling in the construction industry has changed little over recent decades, significant progress has been made in the manufacturing industry, which is serving as a developmental and testing area for automation concepts which may eventually be utilized in construction. The first step in setting up an automated material handling system is provision of a method of automatically identifying the material to be handled. Automatic identification systems which exist or are under development include: bar code readers and wands, radio frequency systems, surface acoustic wave systems, fluorescent markings, optical character recognition, voice recognition, and machine vision.

In addition to automatic identification systems, automatic materials handling equipment is required to actually deliver the material to the robot in a steady flow and in a manner in which the material can be readily utilized. In the construction environment, the handling system must be capable of delivering to a variety of different locations on the job site, often with limited or obstructed access. The system must further be compatible with computer control. The system which is best able to meet these requirements today, and which shows the most potential for expansion in the future, is the Automated Guided Vechicle System (AGVS). AGVS can utilize several different power, guidance and communications systems, and can be easily interfaced with other material handling systems. As well as being a highly flexible material handler, AGVSs are adaptable as robot interfaces and as mobile robot platforms (Boldrin, 1986; and Bose, 1986).

Required sensor technology

The second major technological area considered is that of sensors. Sensors are used essentially for performing the measurement tasks required for an automated machine to perceive and define its environment. These sensors are generally of the 'tactile' or 'vision' type and enable the automated equipment to locate itself, its surroundings, and construction materials and equipment. In addition, sensors allow machines to identify or verify particular objects, complete inspection processes, and provide guidance data to the functional mechanisms which will actually perform the work.

In construction, a large variety of sensors has to be employed. Type and number of sensors required are related to the complexity of the task itself. Additional considerations include the type of output to be measured, the accuracy and repeatability required, as well as the range resolution and response time required. In addition, environmental factors like operating temperatures, humidity, exposure to liquids, dust and corrosives, levels of shock vibration and acceleration need careful consideration. The speed of the operating mechanism and the types of 'noise' to which the system will be subjected are other factors that play a role in the selection of the sensors for any process.

Sensors must also be interfaced to a logic system which analyses the data present and takes action. For monitoring relatively simple processes, personal computers can be used because these are able to use the monitoring information to do higher level diagnostics. Programmable controllers and personal computers for analysis functions are available on the factory floor and could be adapted for construction processes that have features similar to those of factory operations. Additional interfaces with main-frame systems could be provided in the case of interaction with CAD systems.

Most of the sensors that can be used on the construction site belong to the lowest level of complexity. Both the properties of the material being handled and the accuracy required in the handling play an important role in deciding the feasibility of the auotomation/robotization of the work process.

Complexity of required system software

The third technological area considered is that of system software. This is the 'brain', which accepts data and directs decision making. The automated systems developed to carry out this function rely heavily on the concepts of control theory. The system software includes data bases which supply the enormous amount of information required to automate most construction processes. Present thinking in the industrial sector envisions transfer of design information from CAD systems to those data bases supporting the robot. This will require improvements in the areas of data compatibility and integration. The system software must also be capable of processing sensor data and the control signal used to actuate the robotic hardware. Interfaces are required to allow access to a variety of databases and hardware technology systems. Knowledge engineering will be required to allow the automated machine to make decisions based on heuristic search methods.

The robotics software system is assumed to be 'a system which allows robot users to program robot tasks in terms of the key states of the task-instead of manipulator motions.' (Leu, 1985). Such a system consists of two subsystems, a language system and a planning system. The language system deals with the design of syntax and semantics of program statements, and the planning system converts the task-level program to a manipulator-level program. The language system employs textual programming methods (incorporates sensory information) and consists of three levels–the joint level, the manipulator level and the task level, with the task level at the highest level of complexity. For an inherently uncertain and dynamic environment, a process or task oriented approach should be considered. The hierarchy in construction management culminates in the work task. For robot control, however, the level of detail obtained at the task level is not adequate. This necessitates a further breakdown of the work tasks resulting in a hierarchy. This has been the basis of the system developed at the National Bureau of Standards within the Factory Automation Systems Division. The system accepts high level commands and breaks them down into effective behaviour within the context of the conditions reported by the sensory processing system. Each level in this hierarchy requires feedback status from the level below it reporting on the progress of the command to that level. This implies that the sensor technology and system software have a very close working relationship.

At present, the programs used in all commercial robots are at the 'manipulator' level, i.e. the user describes a task in terms of end-effector and joint movements. This type of programming is not easy. It may be tedious for complex tasks and the program statements are not easily comprehensible. Task level programming eliminates these disadvantages since the statements are in terms of the different 'states' of the robot and its environment. The objective of task-level programming is to specify only the goal state of the task through the states of the robot and its environment. In this case, the information about the environment is input from another software program and the geometric information is generated from a CAD database or from visual sensors.

Hardware technology

The fourth of the technological areas included for evaluation is hardware technology. This addresses the actual hardware, which processes the construction material or performs the required function (e.g. inspection of tiles, etc.). A hardware system includes the energy and mobility systems required as well as the processing hardware itself. Presently, a wide variety of actuators and manipulators to execute construction functions exists. These devices, however, concentrate on the use of mobile end effectors, which process the material *in situ* or apply a fluid material to accomplish the required work. Most of the existing systems have been developed for industrial fabrication and require modification for use in the construction industry. Construction poses special problems in terms of heavier loads, longer reaches, and an unstructured and dynamic physical environment.

The use of electric energy is promising to be one of the favourable sources of power to be utilized for energizing construction robots. Robots using electric energy can handle material weights up to 250lbs. based on current technology. Electric actuators do not generate as much power as hydraulic systems. However, their accuracy and repeatability are better. Consequently, electric actuators are normally used where precise work is required and weight restricions allow.

The selection of any type of actuator is dependent on various considerations which include the required speed of performance and the lc..d-carrying capacity. These characteristics are determined by information provided about the task requirements of the robot as well as its working environment. The process requirement includes weight, shape and type of materials which should be handled by the robot. The importance of the working area often limits construction robots to the use of a specific type of energy. It can also indicate the type of articulated system which should be built into the robot body.

The speed and torque of a construction robot is an important attribute since it determines how quickly a robot will accomplish its given work cycle. The speed and torque of a robot is measured by the movement of its wrist, which is generally controlled by the capability of built-in servo motors. For construction purposes, servo motors with higher speeds and torques are needed since many construction processes involve handling heavy materials and travelling long distances in comparison with industrial processes. It is also important to consider accuracy, repeatability, and error tolerance of a robot.

The size, type, and weight of postioned material are the general issues which determine the carrying capacity of a robot. When the load capacity is mentioned, it represents the weight of the robot arm in addition to the maximum load that can be handled when the robot's arm is in its weakest position. The loading capability is a function of the power that can be generated by the servo-system of the robot and its physical structure. Carrying strength of industrial robots can reach several thousand pounds for large robots. However, this maximum capability might not be enough for some construction processes (e.g. precast cladding).

One major issue incorporated into the development of higher loading capability is the development of a capable and lightweight arm. General observations have shown that when the carrying capability is increased, the weight of the robot arm increases as a higher function resulting in restrictions that limit the carrying capacity of developed robots. Research work is required to investigate new approaches for the construction industry.

End effector requirements

The fifth and last technological area considered is that of end effectors. End effectors are the functional devices attached to the end or wrist of a robot arm, which perform the final task of processing the construction material. End effectors are often called end-of-armtooling, and can be classified as hand tools, hand/tool holders, or micro-manipulators. They can be thought of as the equivalent of the human hand, and in many instances these devices are designed to closely resemble a hand, with a palm, fingers and joints. In other cases, there is no resemblance at all to a hand, as in the case of specific function devices, such as a nailer. Although considerable progress has been made in this area, more is needed for adaptation to the construction environment. Fortunately, a significant amount of research relating to this topic is currently underway.

End effectors are categorized according to their functions such as grasping, installation, placing, or removal. This classification focuses only on the applications of the end effectors and is the principal guide used for evaluating the general processes included at the end of this report. In order for end effectors to be developed for applications in construction, the technology must be modified to meet several constraints. Dexterity is one of the first areas that must be improved in order to enable a robot to handle a variety of parts or tools in complex processes (e.g. piping/plumbing). Another fundamental objective deals with developing a quick-change hand or tool holder which should be capable of handling various types of construction materials and accomplishing different conventional tasks (e.g. carpentry robots and steel fabricator robots). Adding higher intelligence through the incorportion of better internal sensing and control devices would also be of great aid in adapting robots for construction processes.

Economic feasibility

The most important factor which will be the driving force for practical implementation of robots in construction sites is economics of robotization. Current robots used in construction sites are not economical for commercial application. Economic benefits of automation and robotization in construction are basically due to: productivity improvement, quality improvement, and saving in skilled labour (Kangari, 1984).

Productivity is the relationship between output and input which can be measured by units produced per man-hours. A robot may be considered more productive if its performance per hour is more than conventional construction methods. Robot suppliers should provide statistics about productivity of robots. These values must be compared with historical data on productivity. Obviously, productivity improvement is not the only factor that pays for the robot. It is also expected that the robot will produce a better or the same quality as traditional methods. However, it should be noticed that cost and quality improvement are directly related. The motivation for future use of construction robot is the saving of labour cost. Saving per year can be calculated by estimating total hours of operation and total direct and indirect cost savings due to the utilization of a robot. A detailed economic analysis using various techniques is described by Skibniewski (1986).

Overall feasibility analysis

The objective of this section is to provide a methodology for feasibility analysis of robotics in the construction industry by combining the above characteristics in a systematic way. Since most of information about construction processes are collected from construction field

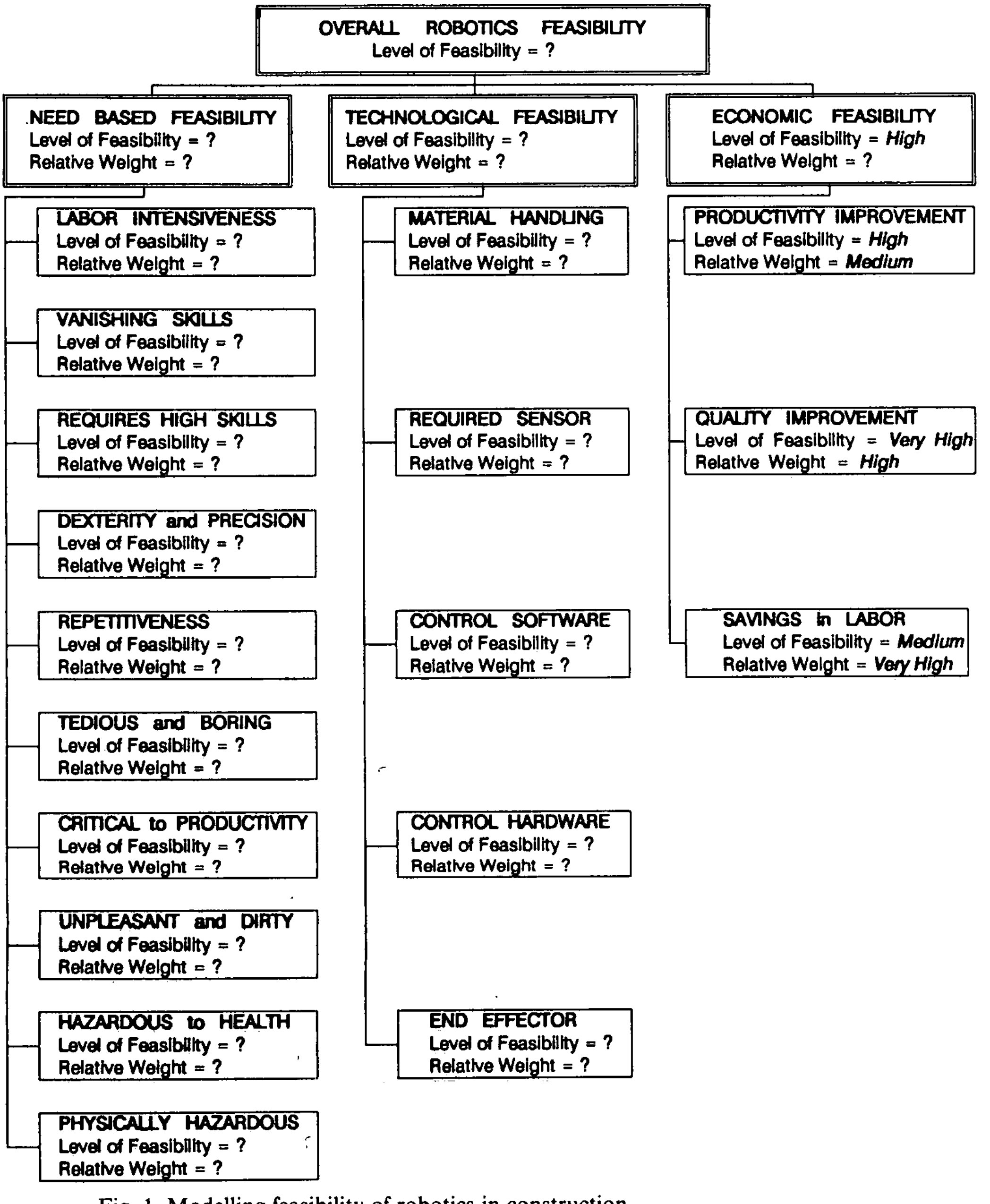

Fig. 1. Modelling feasibility of robotics in construction

experts who have little or no knowledge of numerical evaluation, a fuzzy set model is developed which allows an expert to describe each character in words or sentences in a natural language. For example, a construction expert might describe 'Concrete Surface Finishing' as a 'Highly' repetitive operation under the need-based feasibility.

The model provides a breakdown structure based on the identified factors as shown in

Fig. 1. Such structure allows the user to review all relevant factors and formalize dependency links. This breakdown also serves as a base for further discussions.

In this model each characteristic supporting the feasibility is described in natural language by two factors: level of feasibility, and relative weight factor. The levels of feasibility shows the potential of a construction process in satisfying the requirements of a character. The relative weight factor indicates the importance of a character in its level. The overall feasibility is then calculated by combining these two factors at the lower levels to evaluate the level of feasibility at a higher level. This process is continued till the overall feasibility is calculated.

The fuzzy set evaluation model consists of three parts: linguistic analysis, evaluation, and translation. Each of these components are described in the following section.

Linguistic analysis

A fuzzy set is class of objects with a continuum of grades of membership. The concepts of fuzzy set theory was first introduced by Zadeh *et al.* (1985). A fuzzy set A in universe X is characterized by a membership value of $\mu_A(x)$ which associates with each point in X a real number in the interval [0, 1] as follows:

$$[A] = [x|\mu_A(x)] \tag{1}$$

where [A] is a fuzzy set, $\mu_A(x)$ is a membership value between zero and one, and x is generic element of universe X, which is an integer number between zero and ten. Thus, each word (x) in a natural language can be viewed as a summarized description of a fuzzy set [A]. For example, if the meaning of the term 'Highly Critical to Productivity' is expressed as a fuzzy set, the set might take on a membership value as follows:

$$[A] = [0|0., 1|0., 2|0., 3|0., 4|0., 5|0.3, 6|0.4, 7|0.5, 8|0.7, 9|1.0, 10|1.0] \tag{2}$$

The fuzzy set shown above represents the expert's understanding of the linguistic variable 'Highly Critical to Productivity'. In this fuzzy set, 10 has a strong membership value of 1.0, and 7 has a weaker membership value of 0.5. In the context used above, the values 0 through 10 might correspond to the level of productivity where 0 is very low productivity and 10 is the highest expected productivity for a particular construction process. The numbers 0.0 through 1.0 represents degree of membership of these points.

These definitions of linguistic variables can be provided by the expert or the system designer. If defined by the system designer, the assumption is that these definitions correspond in some way to the expert's intuitive meaning for the terms. In this model, linguistic variables are pre-defined. The objective of the natural language computation is to convert natural language expressions into fuzzy sets.

Evaluation

In this part, the overall feasibility of a construction process is evaluated based on the fuzzy estimates of the components. The model uses the concepts of fuzzy set theory to compose the fuzzy variables into a single fuzzy set as follows:

$$[R] = \sum_i \{[W_i] \odot [R_i]\} \ominus \sum_i [W_i] \qquad i = 1 \text{ to } n \tag{3}$$

where [R] is a single fuzzy set which represents the feasibility of a character in a higher level, n is total number of characters under consideration , $[W_i]$ is a fuzzy set representing relative weight factor of character i, $[R_i]$ is a fuzzy set describing the level of feasibility of character factor i, and $\odot$, $\ominus$ are multiplication and division of two fuzzy sets. This equation uses the Zadeh's extension principle (Zadeh *et al.*, 1985; and Zadeh, 1986), a general method for extending functions over the integers to functions over fuzzy subsets based over the integers. Basic mathematics to calculate the operations, addition, multiplication, and division are defined as:

$$[A]\oplus[B]=[(x+y)|\min\{\mu_A(x),\ \mu_B(y)\}] \tag{4}$$

$$[A]\odot[B]=[(x\times y)|\min\{\mu_A(x),\ \mu_B(y)\}] \tag{5}$$

$$[A]\ominus[B]=[(x+y)|\min\{\mu_A(x),\ \mu_B(y)\}] \tag{6}$$

where $\oplus$, $\odot$, $\ominus$ are addition, multiplication, and division of two fuzzy sets; min is minimim value; and $+$, $\times$, $\div$ are normal arithmetic operations.

To further illustrate this part, let us assume that the levels of feasibility of productivity improvement, quality improvement, and savings in labour for fireproofing operation is expressed by natural language as: high, very high, and medium respectively. Considering equation 3; $[R_1]$ = 'High', $[R_2]$ = 'Very High', and $[R_3]$ = 'Medium'. If the relative weight factors are: medium, high, and very high; then: $[W_1]$ = 'Meduim', $[W_2]$ = 'High', and $[W_3]$ = 'Very High'. In other words, in the expert's opinion the fireproofing operation has a high potential for productivity improvement with a relative weight factor of medium in economic feasibility.

Now, equation 3 is implemented to calculate a fuzzy set which combines these three characteristics. This set represents the level of economic feasibility of automating the process. Then, this set is conveyed from a mathematical form to natural language as described in the following section. This process is continued at all levels till the overall feasibility is evaluated.

Translation

The linguistic approximation model translates back the evaluated fuzzy set, [R], to a lingusitic expression (e.g., high, medium, or low feasibility). This is done by calculating the Euclidean distance from the given fuzzy set, [R], to each of the fuzzy sets, [A], representing the natural language expressions (e.g., high, medium, or low).

The Euclidian distance between fuzzy set [R], and fuzzy set [A] is estimated as:

$$d\,(\mathrm{R},\mathrm{A})=\sqrt{\sum_j [\mu_R(j)-\mu_A(j)]^2} \qquad j=1 \text{ to } 10 \tag{7}$$

where d(R, A) is the Euclidean distance between fuzzy sets [R] and [A], j is an integer between 1 and 10, $\mu_R(j)$ and $\mu_A(j)$ are membership values of element j of the two fuzzy sets. Applying equation 7, the Euclidian distance between fuzzy set [R] and predefined natural language expressions; e.g. low, medium, and high; shown as [A] is calculated. Then, the model assigns the appropriate natural language to the lowest Euclidian distance associated with fuzzy set [R]. For example, if the fuzzy set [R] which represents economic feasibility of a process has a lowest Euclidian distance with a predefined natural language expression 'High', the model assumes that the fuzzy set [R] is translated 'High', which indicates that this process has a 'High' economic feasibility level for robotization. This process continues till the overall feasibility is evaluated in natural language.

A knowledge system is developed based on these principals. Insight 2+, a microcomputer shell program (Insight 2+ user manual, 1986) is implemented. This system allows the feasibility analysis of automating various construction processes in a very friendly fashion by natural language expressions.

Summary and conclusions

The use of automation and robotization in industrial production is a well established issue and rapidly expanding. The close relationship of prefabrication for construction to industrial production has made prefabrication the logical area for initial efforts at automation of construction processes. The reduction in the numbers of highly skilled craftsmen available for work on the actual construction site, the increase in sophistication of construction materials, and the constant demand for increase in quality and reduction of construction time all indicate that greater degrees of automation will be required in the construction industry. Significant advances have already been made in both large-scale and small-scale applications. Rapid advancements in computer technology, in both hardware and software, will accelerate construction automation. Increases in the use of automation for prefabrication will generate an understanding and familiarity with these concepts which will help generate a wider acceptance. A basic requirement for these advances is the recognition, at the design level, of the potential areas in which automation and robotization will yield productivity benefits.

Truly robotic earthmoving equipment of the open loop variety would appear to be feasible in the near term. The major factor deterring the realization of this type of robotization would appear to be needed. The desire to remove the man from the control loop does not seem to be justified except for equipment operating in extremely hazardous environments.

It is important to note that maintenance of a correct relationship between the speed of processing and the speed of material delivery is essential to the effort to automate construction processes. What benefit is there to developing a high-speed automated construction system if it is standing idle due to lack of material, connectors, or tools? The requirements for material handling must be considered at all stages, from project planning and design, through final inspection of the completed job. The systems developed for manufacturing will undoubtedly serve as a foundation for the development of similar systems in construction. Some of the principles of material handling systems in manufacturing can be applied directly to construction: the need for management commitment to the program from the top to the bottom, standardization of databases and communications devices including CAD, the requirement for automated material identifications systems, and the availability of proven automated material handling equipment (e.g. automated guided vehicle systems).

Tasks which involve the application of fluids or fluid like materials are better adapted to material handling capabilities of existing robotics technology. Inspection tasks appear to be well adapted to automation and robotization. Operations of unsafe environments offer excellent opportunities to apply robotics. Production of certain processes can be enhanced by using semi-automation to reduce the skill level required of the human worker or operator. Research to develop a viable system (i.e. a job site metrology) to allow job site robots to determine position is a prerequisite to highly autonomous robot operating on the construction site.

This paper provided a methodology for feasibility analysis of robotics in the construction industry. Major factors in robotization of construction processes are identified as: need, technology, and economics. Examination of the processes which rank high based on the needs criterion confirms the assertion that dangerous or unhealthly process environments provide an important basis for robotization. For technically complex situations, the need must result in such large economic benefits that the payoff is sufficient to offset the large developmental and market penetration costs. One example of such a process is industrial piping. It is estimated that up to 40% of the costs of industrial plants (e.g. petro-chemical, power generating) are tied to piping. A savings in the fabrication or installation of piping amount to 5% would yield a significant reduction in plant cost. Therefore, economic benefits associated with improved production and quality on large industrial plants may support robotization for processes which are weak candidates based purely on the hazardous environment criterion.

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