TASK IDENTIFICATION FOR CONSTRUCTION AUTOMATION

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ABSTRACT

Recent work in construction automation has proceeded in two directions: the development of automated and robotic equipment, and the identification of construction tasks that are good candidates for automation. Previous task identification studies have focused on total automation using robotic manipulators. However, approaches to automation in manufacturing and the success of partially automated heavy construction equipment indicate that this focus is too narrow. To avoid a priori assumptions regarding the extent of automation and the configuration of automated equipment, a two step procedure for task identification is proposed. The first step, *preliminary selection,* is based solely on the potential for the anticipated benefits of automation. In the second step, *conceptual design*, an interdisciplinary team examines the various ways in which each of the previously selected tasks could be divided between man and machine. In this paper, recommendations are made regarding the use of benefit data in preliminary selection, the composition of the design team is addressed, and a framework to guide the design effort is presented. The two step task identification procedure proposed here should help ensure consideration of the full spectrum of approaches to automation.

1. INTRODUCTION

In the last two decades, manufacturing industries have made increasing use of a new type of automated equipment, the robot. While not the panacea they were once thought to be, robots have been used successfully in a variety of manufacturing applications. This, combined with concern about construction productivity, has led many researchers to investigate applications of robotic technology to construction. There has been a significant investment in the development of automated and robotic equipment for use in construction. Much of this work has been carried by the research labs of the major Japanese firms. These firms have a continuing relationship with owners which allows them to look beyond the bottom line of a particular project. In the U.S., however, construction firms do almost no research, and there is only limited funding available from other sources. Equipment manufacturers have research and development groups, but these are primarily geared to the improvement of existing tools and equipment, rather than the development of new equipment. The high cost of machine development and the scarcity of research funding has led some researchers to focus first on identifying construction tasks for which automation is most likely to succeed.

Five task identification studies have been undertaken to date. Warszawski assessed the feasibility of applying robots to ten basic activities required in building construction [1]. Halpin, Kangari, Abraham, and McCahill addressed the costs and benefits of applying robotic technology to 33 processes selected as good candidates for robotization [2]. Alonso Holtorf postulated that a series of economic indices could be augmented by a measure of "physical susceptibility" to determine the building sub-systems best suited for automation [3]. Skibniewski and Russell have outlined a method to assess the appropriateness of a machine for a particular task; they suggest comparing the results of this method with a companion evaluation of human performance [4]. The Construction Industry Institute (CII) has recently undertaken "the identification and prioritization of activities for construction automation" [5]. In general, the studies completed thus far conclude that construction tasks which require the treatment of continuous surfaces are most feasible to carry out with robots, while those requiring the positioning and fastening of discrete objects are the least likely candidates for automation.

The CII study may signal the start of increased U.S. industry involvement in construction automation. It is therefore important to identify any limitations of previous studies. The studies described above suffer from two restrictions on their scope. First, with the exception of the work by Alonso Holtorf, all are limited to the potential uses for *robots* in construction. The participants have started with a preconceived notion of what a *robot* is and what a *robot* can do. While the results are valid assessments of the possible uses of *robots* on construction sites, the more general issue of the potential for *automation* in construction is not addressed. A second drawback of previous studies is an emphasis on applications in which a machine completely replaces human labor. For the foreseeable future, human labor will be required for all construction processes (except perhaps those in extremely dangerous environments – reactors, deep sea, space). Focusing only on complete automation therefore seems unduly restrictive.

2. A GENERAL APPROACH TO AUTOMATION

The ASCE's definition of productivity – achieving *total cost effectiveness through the optimal use of resources* – provides the motivation for a more general approach to automation. Much of the current emphasis on robotics in construction stems from the search for a machine that can replace a construction worker. However, this may not represent the optimal use of resources. A less constrained approach considers automation not only as the replacement of man by machine, but also as a way to develop new and more sophisticated tools for construction workers. A person's vision and judgement provide a means of sensing and control that for many tasks is far superior to anything with which a machine could be equipped. On the other hand, machines can be designed to handle loads much greater than a person is capable of moving. The goal in the planning and design of automated equipment should be a division of labor between man and machine that makes best use of the abilities of each. Knowledge of human capabilities and available technologies, an understanding of construction methods, and a willingness to consider a various degrees of automation will be required.

A task identification study should select the construction tasks for which automated equipment is most likely to improve productivity. Because research funds are limited, this effort should require only a modest investment, leaving sufficient resources for the development and implementation of prototype machines. There must be a compromise between the quality of the selection process and its cost. Previous studies have limited the scope of the task identification effort by focusing on automation using *robots*. When a more general approach to automation is taken, task identification must be carried out in a way that (1) can be accomplished with limited resources and yet (2) remain free from restrictions on the type of technology under consideration. The first of these requirements implies the need for a *preliminary selection* of tasks; the second can be realized by incorporating *conceptual design* into the task identification process.

3. PRELIMINARY SELECTION

The purpose of preliminary selection is to reduce the number of tasks that will be considered at the conceptual design stage. Halpin et.al. accomplished this by asking construction practitioners which processes they felt were good candidates for "robotization" [2]. This method is too restrictive for the general approach to automation advocated here, as it incorporates participants' implicit assumptions regarding degree of automation and configuration of automated equipment. Any selection method based on the technical feasibility or cost of automation prior to explicit consideration of the variety of ways a task can be divided between man and machine will suffer the same limitation.

What about estimating benefit? Estimation of benefit requires knowledge of the intended performance of a proposed system, information which would be available only after the completion of a conceptual design. An alternative is to consider the *potential* for benefit. Whereas benefit depends on both current practice and the performance of a proposed (as yet undesigned) system, the *potential* for benefit depends only on current practice and the anticipated benefits of automation in general. Construction tasks with a high *potential* for benefit could be identified prior to investment in conceptual design.

3.1 The Benefits of Automation

Automation in manufacturing has provided the following benefits: reduced labor requirements, increased production rate, improved quality, improved safety, reduced scrap, stabilized labor requirements, and improved corporate image [6,7]. Which of these are likely to be important in construction? Construction is a very labor intensive industry. Particularly in light of current concern over potential labor shortages, reduced labor requirements could be an important benefit of automation. Time is critical in construction, as indicated by the use of bonuses/penalties for early/late completion. Even if labor costs remained constant, increased speed of construction would be beneficial. While construction quality "is generally considered quite acceptable, if skilled craftsmen are available" [5], a shortage of skilled labor would make it difficult to maintain quality. Automation could help maintain construction quality by achieving a consistent output over time and by providing built-in inspection. Finally, an improvement in construction safety could be a major benefit of automation. In addition to reducing the rate of injury, improved safety could make the construction more appealing to a shrinking labor supply.

Construction is a project-based industry subject to large fluctuations in demand; such factors as reduced inventory and stabilization of labor requirements will be of less importance than in manufacturing. For most tasks, reduction in scrap would require changes in materials and design, rather than changes in equipment only. While the use of automated equipment could affect corporate image, it is nearly impossible to determine in advance the extent of this benefit. Reduced labor requirements, increased speed, improved quality, and increased safety thus appear to be the most important ways in which automation could improve construction productivity. The potential for benefit through automation will be high when the potential for these improvements is high.

3.2 Assessing the Potential for Benefit

Two approaches could be followed in order to identify construction tasks for which there is a high potential for benefit from automation. The first relies upon personal experience. The participants in construction projects could be asked to list construction tasks for which they feel there is a high potential for benefit. This approach to gathering information is similar to that used in [2] and [5]. Its main advantage is the opportunity to solicit comments and explanations. A drawback, especially for studies of broad scope, is the time required to obtain unbiased results. An alternative is to use statistics compiled industry-wide or by individual firms. This approach is similar to that taken in [3]. If the appropriate statistics were readily available, preliminary selection could be accomplished fairly quickly and at minimal cost. A further advantage of this approach is that it draws upon on a broader base of information than the experiences of selected individuals. However, the ability to ask why a particular task has a high potential for benefit is lost.

The use of statistics in preliminary selection was examined in [9]. A review of available data showed that for some of the benefits of automation, relevant statistical information is not readily available. Like automation, preliminary selection must make best use of all available resources, incorporating information from surveys and interviews where existing statistical data is insufficient. The following recommendations for benefit indicators are discussed at greater length in [9] –

Reduced labor requirements: High potential tasks are those that account for the largest labor costs. If estimating is computerized, quantity take-off information provides the best source of data. If not, use a survey of estimators. Wage rates and apprenticeship durations are useful indicators; these are highest for the mechanical and electrical trades. Superintendents and foremen can determine if high labor costs are due long waits for materials, tools, or workspace.

Increased speed: High potential tasks are those that occur on/near projects' critical paths. If scheduling is computerized, critical path information provides a good source of data. If not, use a survey of schedulers, with supplemental information from project managers and superintendents. Careful checks on the consistency of results with changes in time and location are necessary.

Improved quality: High potential tasks are those that require rework or repair due to poor construction. Due to the lack of published information, interviews with superintendents and foremen should be used in assessing rework. With respect to repair, leaking roofs and problems with concrete work are prevalent. The AEPIC database [9] could be used for additional repair data.

Improved safety: High potential tasks are those for which accidents exact the highest costs (medical, compensation, and emotional). Worker's compensation rates provide the most comprehensive source of information. Rates should multiplied by trades' hours. High injury rates indicate a high potential for benefit for trenching, excavation, roofing, work done on scaffolding or ladders, and tasks requiring repetitive motions. Surveys or interviews with safety officers, project superintendents, and foremen should be used to obtain further information .

Using these sources of information, high potential tasks for each of the four benefits of automation can be found. The sponsor of a task identification study will determine the scope of the study, structuring the preliminary selection procedure. For example, a labor union might place more emphasis on the benefits of safety, while a group of building owners might be more concerned with quality. A manufacturer of concrete blocks would be interested primarily in the installation and finishing of concrete block or the installation of mechanical and electrical systems when concrete bock is used. Statistical information regarding labor costs and critical paths would be of limited interest, since the scope of the study is already restricted. However, input from craftsmen and project supervisors with experience using concrete block would be essential. In general, studies with a narrower scope will rely more heavily on information obtained through surveys and interviews.

4. CONCEPTUAL DESIGN

A general approach to automation requires selection of the "best" combination of human and machine resources for the particular construction task under consideration. While there may be some uncertainty about the abilities of human resources, the greatest unkowns will be the costs and capabilities of as yet undesigned machines. At least a conceptual design will be required before these can be estimated. The conceptual design should include a description of the machine's functions, a sketch of the proposed configuration, estimates of the forces and movement ranges required, and preliminary recommendations for major components. Given the current state of automation technology and of construction, few machines will be intended to operate autonomously. Instead, construction operations will be carried by systems of men and machines. So that the performance of the system as a whole can be assessed, the conceptual design should indicate the functions to be performed by the machine operator and other workers, and the impact the proposed system will have on other construction operations.

4.1 The Design Team

The conceptual design process requires knowledge of construction, human abilities, and the design of automated machinery. Equally important is the ability of people with various backgrounds to work together to generate creative ideas. In the literature on group methods for the generation of new ideas, it is generally recommended that groups have 5 to 15 members, and that a designated group leader serve as a facilitator, preventing disputes between members and encouraging the flow of new ideas.

Knowledge of construction processes, both at the detailed level and in the context of the overall project, is important for the conceptual design effort. Craftsmen are the best source of detailed information about current practice. The design team should include an experienced craftsman from each trade that currently carries out the task under consideration. Knowledge of the overall project can best be provided by an experienced superintendent or project manager. Because the conceptual design effort will address systems in which the craftsmen's role may be different from existing practice, the team should include a member with a background in ergonomics. The conceptual design effort clearly requires the input of people experienced in the design of automated equipment. Two designers should be included in the design team: one whose specialty is mechanical design, the other more versed in sensing and control. Both should have prior experience with the design of partially automated systems in which the operator plays an important role. Depending on the task under consideration, it may be helpful to include someone familiar with the construction materials and tools used in current practice.

It is important that the leader of the conceptual design team be able to put aside personal opinions about the "best" solution to a problem. While a broad background is desirable, the ability to effectively guide the design team is the most important criterion for selection of a team leader. How and from where the team members are selected will depend on the sponsor of the study. Sponsors may encourage the participation of their own employees. Participants not already under contractual obligation to the sponsors will be providing consulting services, and should be treated compensated appropriately. In return, sponsors would own the ideas produced in the conceptual design process.

4.2 Force and Displacement Framework

The design team will be composed of members with diverse backgrounds. How will this group go about the process of conceptual design? As noted above, a variety of methods have been proposed to help groups generate ideas. Any combination of idea generation methods may be used. An additional approach, intended to facilitate investigation of the division of labor between man and machine, is proposed here. It is based on the forces and displacements required to carry out construction work.

Forces can be classified in many ways – by line of action, by magnitude, etc. An examination of existing construction tools and equipment suggests a classification based on function. Forces are required for the *support*, *operation*, and *transport* of tools and equipment in order to carry out construction tasks. When using a hand tool, a person generally provides the forces required to *support* the tool, the forces required in *operation* of the tool, and the forces required to *transport* the tool from location to location. In the case of portable power tools, while the user must generally *support* and *transport* the tool, energy from the power source is transformed by the tool into the forces required for *operation.* In heavy equipment, not only *support* and *operation,* but *transport* forces as well are typically provided by the equipment, rather than the operator.

Classifying forces according to function is useful because it highlights the different divisions of labor in existing tools and equipment. More importantly, the range, accuracy, and duration of force required will generally be different for the various functions within a task. The best way to cause these forces will therefore generally be different as well. Displacements can similarly be considered by function – those required to achieve *initial position*, those required for *operation*, and those required for *transport*. Again, the specifications or requirements for the range, accuracy, and speed of the displacements required in a particular task will vary with function.

Whether a force is applied in support, operation, or transport, determining the appropriate mix of human and mechanical labor requires consideration of three further issues: *generation*, *control*, and *sensing*. Any or all of these may be accomplished by man or by machine. Displacement can be considered at this level as well. However, in most tools and equipment, it is force that is generated; displacement results from the behavior of the environment as it is acted on by this force. It is therefore reasonable to look at how the direction of displacement is determined, that is, what provides the *constraints* that ensure motion along a desired.

The third level of the framework is implementation. At this level, the various ways of generating forces, constraining displacements, and accomplishing sensing and control are compared, and the best selected. Both human capabilities and existing technology must be considered. The design team should have the required expertise in both areas. Figure 1 summarizes the force and displacement framework described here. Its main purpose is to focus attention on the various ways in which the abilities of man and machine can be combined, whether on or off-site. The framework will be most valuable at the start of a design session as an initial tool to provoke thought, and at a design session's conclusion as a way of comparing proposed designs and identifying areas that have been neglected. The following section provides an example to be used at the start of a design session to introduce the idea of division of labor.

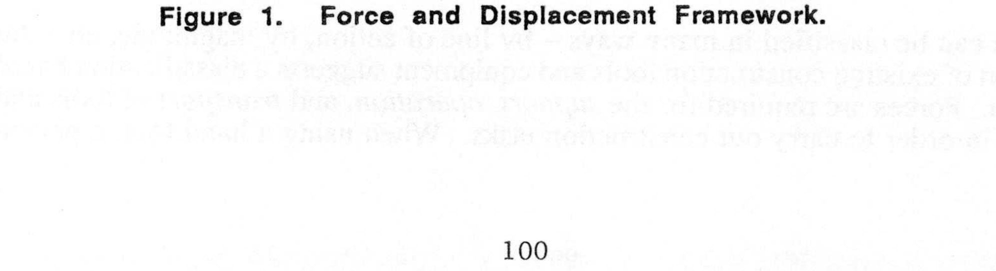

Figure 1. Force and Displacement Framework.

5. DIVISION OF LABOR – AN EXAMPLE

In this section, the tools that can be used to make a hole in a existing piece of material are discussed in terms of division of labor. Consider first the most basic way to put a hole in a piece of material – a hammer and punch. The user places the sharp end of the punch against the material at the point where the hole is to be made, holds the punch vertically, and strikes the blunt end with a hammer or mallet. Support, operation, and transport forces are all generated by the muscles of the user, as are the constraints on displacement required for initial positioning, operation, and transport.

With a power drill, the tool's power supply frees the user from the need to provide operation forces. Support and transport forces must still be generated by the user, along with all constraints on displacement. In a standard power drill, the user provides the required sensing (through vision, touch, and hearing) and control (through the adjustment of support forces and trigger displacement). However, in a drill equipped with an automatic clutch, the control of operation force is divided between the user and the tool. The user adjusts the trigger displacement as for a standard drill. When the output torque reaches the cutoff level (for example, when the drill bit is jammed), the clutch disengages (slips), automatically reducing output torque to zero. Control at high torque is thus accomplished mechanically.

A portable drill with a magnetic base relieves the user of still more labor. Support and operation forces are provided by the tool. The user need only provide the transport forces required to move the drill from location to location (or to bring material to the drill). The user must still control displacements so that the desired initial position is achieved. However, in operation, the slide on the base constrains the displacement of the drill be along to lie along one axis. The user controls motion of the drill along the axis of the slide by rotating the handle on the side of the base. Use of a stationary drill press, such as could be found in a machine shop, requires the same division of labor as described here. However, the drill press remains in one place – transport is always of material to the drill press.

Within a machine shop or fabrication plant, holes may also be made by using a milling machine. Support and operation forces are provided by the machine; the user must transport material to the machine's table, and the table to the desired initial position. The machine's slides or ways, however, constrain the motion of each degree of freedom, simplifying positioning. If the machine is equipped with power feeds, the user does not need to provide transport forces once the material is placed on the table, but still must sense and control the motion of the table. With a numerical control (NC) or computer numerical control (CNC) milling machine, the user plans the sequence of operations in advance, encoding the required machine movements on a tape (NC) or in a computer (CNC). The user must transport the material to the machine, but once the material is secured to the machine's table, all functions are accomplished by the machine.

Finally, in an untended machining center, drilling a hole can be accomplished entirely by machine. Material is transported from storage to the machining center automatically (using an automated guided vehicle or some other automated system), and placed on the table of the milling machine (perhaps by a robot). Drilling of the hole is accomplished by a CNC or NC milling machine. The material is then removed automatically, and the process repeats.

All the tools described above are currently used; the existence of more highly automated systems has allowed certain tasks to be accomplished which would have been impossible otherwise, but has not made simple hand tools obsolete. The combination of the abilities of man and machine that is most productive for a particular application depends both on the physical characteristics of the task and on economic factors. This example provides a good illustration of the different ways that labor can divided between man and machine for a particular task. Furthermore, it introduces issues of control and sensing in the context of tools and equipment that are likely to be familiar to all members of the conceptual design team. As part of an introduction to the design session, the example could be used by the leader of a design team to provide team members with a common set of terms helpful in describing proposed designs, and a framework within which proposed designs can be discussed.

6. SUMMARY

This paper has described a method of task identification compatible with a general approach to automation. The method differs from those in previous studies in that it does not require initial assumptions regarding either the extent to which a task will be automated or the technology with which it will be automated. Instead, these issues are addressed explicitly through the incorporation of conceptual design within the task identification procedure. In order to reduce the number of tasks to be considered at the conceptual design stage, preliminary selection is carried out based on the potential for benefit through reduced labor, increased speed, improved quality, and improved safety. The advantage of the proposed two step task identification procedure is that it encourages the consideration of a wide variety of approaches to automation. It not only results in the identification of tasks for which automation will be the most beneficial, but provides conceptual designs of the machines required. Its disadvantage is the effort required, particularly in conceptual design.

7. REFERENCES

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