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DESIGN PRACTICES TO FACILITATE
CONSTRUCTION AUTOMATION

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Research Report 183-11

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DESIGN PRACTICES TO FACILITATE CONSTRUCTION AUTOMATION

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A Report to
Construction Industry Institute
The University of Texas at Austin

Under the Guidance of
CII Project Team 183
Design Practices to Facilitate Construction Automation

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EXECUTIVE SUMMARY

Automation in the construction industry involves the use of mechanical and electronic means to achieve automatic operation or control to reduce exposure, time, or effort while maintaining or improving quality. Contractors use automation to reduce costs and schedule, improve production, quality, and safety, and gain related project benefits. Automation in construction, however, has not kept pace with other industries and remains a predominantly labor-intensive activity.

Many factors limit the use of automation in construction. Cost, availability, and applicability of automated technologies, along with the knowledge and training required to operate the technologies, are obstacles to implementation. The design of permanent features and the means used to communicate the design may either inhibit or prohibit the use of automated technologies during construction.

CII created the Design Practices to Facilitate Construction Automation Project Team (PT-183) to investigate this issue. The resulting research has identified design practices that facilitate the implementation of automated technologies and exposed barriers to and limitations of addressing automation in design. Recommended design practices to facilitate the use of construction automation include:

- Conduct constructability reviews during the design phase that incorporate consideration of construction automation.
- Standardize design features and elements.
- Provide adequate clearance for automated technologies to operate.

- Prioritize design objectives and compare design alternatives.
- Use electronic documents and make the documents available to the contractor.
- Consider the capabilities and limitations of the automated technologies.

Numerous factors hinder the consideration of automation, including the structure of the industry, a lack of applicable knowledge by design professionals, and the limitations of the technologies themselves. To implement the findings, the industry and project participants need to:

- Provide for efficient, timely exchange of project information between constructors and designers.
- Conduct constructability reviews as a means to facilitate the application of construction automation knowledge in the design phase.
- Modify traditional contracting arrangements to allow for expanded interaction between designers and constructors.
- Recognize that designer compensation may need to be modified to provide incentive to consider construction automation in design.
- Expand education and training of designers regarding construction automation.

This research report describes the research effort undertaken for the study. The findings of the study are also available on the Emerging Construction Technologies website (www.new-technologies.org/ECT/Index.html).

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CHAPTER 1

INTRODUCTION

The construction industry is one of the largest production industries in the United States, amounting to nearly ten percent of the country's Gross Domestic Product (GDP). In addition to being very large in size, construction is an industry that is quite diverse and complex, encompassing many different disciplines and trades that join together to build projects which vary widely in size, type, and scope. It serves all other industries, providing the infrastructure for our daily lives. The nature and pace of the industries that it serves place a significant burden on the construction industry to complete projects at minimal cost, with high quality, and in a safe, efficient, and timely manner. While the industry's size and complexity often make it difficult to change, the demands of its customers continue to shape the way it looks and operates.

In recognition of the demands placed on it, the construction industry continues to look for ways in which it can improve quality and be more productive, safer, and cost efficient. Other work industries have made significant gains in these areas over the past several decades. The gains that have occurred are due in large part to the development and implementation of innovative technologies. New materials, tools, work processes, and computer and electronic technologies have been embraced by other industries and play a major role in their success. Construction has developed and incorporated new technologies for its benefit as well. New construction technologies are available that allow for more efficient, safer construction work leading to a high quality product. This is especially true of technologies that automate the construction process. Automation provides opportunities for the construction industry to not

only successfully meet the demands of its clients, but also present itself as an attractive industry in which to work.

The primary objective of automation is the improvement of the work environment and freeing of workers from dangerous and simple, repetitive tasks. In this regard, automated technologies promise a more productive workplace where human energies can be directed at processes that require the thought, attention, and motion that cannot be replicated by machine. Expanded use and development of new automated technologies are looked upon as critical to the continued growth and competitiveness of the construction industry.

Many new construction technologies exist, but implementation of some has not been widespread. Additionally, some construction activities have become highly automated while others remain very labor intensive. The reasons for the lack of diffusion and implementation of automated technologies throughout the construction process are varied. Contractors have cited cost effectiveness, availability, and applicability of the technologies as obstacles to their widespread use. The availability of skilled workers to operate the technologies can also be a barrier to effective implementation. Workers competent in operating new, complex technologies are often unavailable, and the training can be prohibitively expensive. The size and diversity of the construction industry may be an impediment to widespread application as well. Small-sized companies, which make up the majority of firms in the construction industry, often lack the available funds to purchase the technologies and train their workers to operate the technologies. Technologies that are expensive and which require significant resources to support remain accessible only to larger construction firms.

Besides the barriers and limitations to implementation that exist within the construction firm and workforce, another barrier can be the design of the project being built. The design of

the project influences the extent to which automated technologies are used during construction. The capabilities of automated equipment are constrained by the physical aspects of the design. The site conditions and design features may be the overriding limiting factors as opposed to construction-related barriers. Furthermore, some technologies require electronic input in specific formats to make their use practical. Without suitable communication of the design, their implementation may not be feasible. Minor modifications to the design and the format in which the design is communicated can potentially enhance the use of automation and lead to improved project performance. Recognition of this relationship was central to the successful integration of automated technologies in the manufacturing industry and the subsequent benefits which the industry received. “The general lesson to be learned from the introduction of robotics in the manufacturing industry is that robotic devices must be considered as an integral part of the design and production process” (Cusack, 1994).

Critical to addressing construction automation in the design of a project is knowledge about how a project’s design impacts the implementation of automated technologies during construction. It is believed that knowledge about available automated technologies, and how to facilitate their use through design, is absent within the design community. This knowledge must be developed in order for designers to understand the types and capabilities of available technologies, and to create designs that promote their use. The CII Design Practices to Facilitate Construction Automation Project Team (PT 183) was formed to investigate the impact of design on the use of automated technologies during construction and to develop design practices that can facilitate their implementation.

CHAPTER 2

LITERATURE REVIEW

Automated Technologies: Current and Future

Current knowledge related to automated construction technologies and their use centers primarily on the technologies themselves. A description of many available technologies can be found in IAARC's publication "Robots and Automated Machines in Construction" (IAARC, 1998). This text provides the technical characteristics, features, work execution records, and usage conditions of seventy-six robots. It describes robots designed for demolition, surveying, excavation and earthmoving, paving, tunneling, concrete placement, steel erection and welding, and other construction activities. Other available literature contains many more descriptions of automated construction technologies that are currently available for use or are prototypes in development (e.g., Kangari and Yoshida, 1989; Moselhi, et al., 1992; and Seward, D., 1992).

Many of the automated technologies available have been developed in Japan, whose culture and environment fosters development and implementation of new technologies. "In the United States, the objective of research conducted under government sponsorship at research universities and government laboratories is primarily to obtain new knowledge and to develop new principles. In Japan, the objective of the contractor R&D institutes is primarily to verify and improve engineering designs and construction procedures throughout experiment and to assure the safety of Japanese constructed facilities." (Gann, 1996). Cousineau and Miura (1998) provide a comprehensive description of the development and application of over 100 construction robots and five automated systems in Japan, and conclude that the impact of

robotics in Japan “has already begun to show measurable improvements in quality, productivity, and safety in construction”.

Literature also exists that describes the research and development of specific automated construction technologies that have taken place. For example, Hughes, et al. (1989) conducted research to develop enhancements to a pipe manipulator to allow for increased automation. The researchers concluded that automated control enhancements for pipe erection offer faster and more accurate motion. In another effort, a group of researchers from the Construction Automation and Robotics Laboratory at North Carolina State University developed a robotic excavation and pipe installation system (Lee, et al., 1999). The system is comprised of a backhoe excavator with a pipe manipulator attachment controlled by hydraulic actuators. The initial prototype proved to effectively place pipe in a trench without the need to place workers in the trench, and required fewer man-hours per linear foot of completed pipe than traditional construction methods. A significant amount of additional literature is available that describes similar efforts to research and develop technologies for other construction activities, such as masonry construction (Chamberlain, 1994) and for interior finishing work (Warszawski and Navon, 1991). For building construction in particular, almost all building construction operations can be performed by robots that perform the following: excavation, assembling, interior general purpose work, floor finishing, and exterior wall finishing (Warszawski and Sangrey, 1985). These are the primary activities undertaken for the construction of buildings and guide the conceptual design of future automated technologies. Significant efforts have also been undertaken to automate heavy/highway construction. Automated control technologies of heavy equipment using GPS, for example, are becoming commonplace on large earthmoving and paving projects.

Feasibility and Impact

The feasibility of using automated technologies and the associated impacts are important factors that should be addressed when considering technology implementation. In a study of the need for and feasibility of robotization in construction, Kangari and Halpin (1989) identify eight activities and key considerations central to the development of automated technologies:

1. Tasks that require assembly and installation of objects (particularly heavy prismatic solids) are not feasible using the present robotics technology.
2. Tasks involving the application of fluids or fluid-like materials are better adapted to the material handling capabilities of existing robotics technology.
3. Construction activities related to the preparation of processing of large surfaces are well adapted to construction automation, particularly when no material must be applied to the surface to be processed.
4. Inspection tasks appear to be well adapted to automation and robotization.
5. Operations in unsafe environments offer excellent opportunities to apply robotics or teleoperation.
6. The application of robotics to processes with significant economic potential may be justified if the synthesis of existing technologies supports a high probability of successful development.
7. Although processes involving assembly and processing of solid objects are poorly suited to “closed loop” robotization, certain tasks within such processes may be candidates for automation with human support.

8. Production of certain processes can be enhanced by using semi- or partial automation to reduce the skill level required of the human worker or operator.

With regards to specific technologies and activities, one study evaluated the feasibility of utilizing an interior finishing robot in building construction (Warszawski and Rosenfeld, 1994). The researchers found that the machine is most efficient when there is ample room for it to maneuver and when the work is distributed. Labor savings from use of the robot was estimated to be between 60% and 90% for typical tasks.

Another study of productivity associated with the slab-on-grade construction also found improvements resulting from automated technology implementation (Moselhi, et al., 1992). When compared to conventional construction methods, automation of finishing tasks allowed a reduction of the finishing crew size by 30%. When the concrete placement activities were automated, the crew could be reduced by 33%. When both finishing and placing activities were automated, the total activity duration was reduced by 60%.

In another application, the use of automated technologies for excavation grade control has been shown to reduce costs significantly, in some cases by over 80%, and achieved subgrade thickness tolerances of 2% as opposed to 10-20% otherwise achieved on normal work (Paulson, 1985). It should be remembered, however, that the feasibility is highly dependent on the site parameters. The conditions present on one project may be more conducive to implementation than those on another project.

Skibniewski (1988) provides a comprehensive analysis of the impact of robotics implementation in the construction industry. The analysis focuses on both the technical feasibility and economic feasibility of the robotization of two surface treatment operations:

sandblasting and concrete formwork cleaning. Technical feasibility is based on an ergonomic evaluation of individual steps taken to accomplish the given work task, and by analysis of the requirements for robot control and process monitoring. Economic feasibility is based on the benefits and costs associated with the technology's development and field implementation. It is concluded that there is a strong technical and economic potential for automating the sandblasting process, with significant impacts seen in worker health (removal of workers from the exposure to silica dust), increased productivity, and reduced labor expenditures. The cleaning of concrete formwork using automated technologies was found to be reasonable economically and have significant technical feasibility. Another analysis by Skibniewski and Hendrickson (1990) of automation with respect to road construction and maintenance tasks revealed that the repetitiveness and moderate sensory requirements of these tasks provide significant potential for automation.

Barriers and Limitations

Attempts have been made to identify and characterize the barriers within the construction industry to the use of automated technologies. Based on a survey of construction companies, universities, and other research organizations, Warszawski and Navon (1998) identify four reasons why automated technology use is limited in construction:

1. Existing robots are not well adapted to building construction;
2. There are problems associated with the conventionally designed building;
3. It is difficult to justify robot employment economically; and
4. There are managerial barriers.

It is particularly noteworthy that the design of the project is recognized as a barrier by all of the survey participants. With regards to the design, the researchers suggest that “attention should be given to the provision of large unobstructed interiors, exterior surfaces with well-adapted opening details, and poorly selected construction technology.”

Beyond the physical barriers of the site conditions and capabilities of the equipment, introduction of automated technologies into construction faces barriers associated with human factors. Obstacles associated with the mindset and culture of the workers who operate the machines and the personnel who manage their use also exist. A survey of large construction companies (Navon, et al., 1993) revealed that most construction personnel feel that labor-management relations would be worsened by utilizing automated technologies for construction tasks. The substitution of machines for humans can be negatively received by workers since it is sometimes viewed as an attempt by management to eliminate jobs. Additionally, increased implementation was viewed as dependent on a change of contractor attitudes toward the positive regarding advanced technologies. Utilizing unknown and sometimes unproven technologies can be a difficult decision especially when significant contractual obligations regarding cost and schedule must be met.

The pursuit and use of automation is also dependent on the extent to which it satisfies the demands placed on those involved in a project. A project manager, for example, will undertake a specific activity if there is a need for that activity to be accomplished. Similarly, automated technologies will be utilized if a demand for them exists within the construction industry. In a study of the ability of automation and robotics to satisfy the demands placed on managers, owners, workers, and society (Everett and Saito, 1996), the demand for these technologies was

found to be weak in the United States. In fact, resistance to their use was shown to be greater than the satisfaction received from their use.

Influence of the Design

Limited research has been conducted to understand or quantify the relationship between a project's design and the ability to automate the construction process. In their investigation of automated technologies used for interior finishing work, Warszawski and Rosenfeld (1994) state that one of the impacts to the economic feasibility of the technologies is a project design that takes into account the constraints of robotized construction in terms of materials technology and space dimensions. As stated previously, it is also suggested that to facilitate the use of automated technologies for building construction, the design should contain large unobstructed areas and exterior surfaces with well-adapted opening details (Warszawski and Navon, 1998). No other studies were found that explored the influence of the physical aspects of a design on construction automation in detail.

The process by which a project is designed and constructed has also been considered. Everett and Slocum (1994) compare construction and manufacturing with regards to the relationships between product design, process design, and fabrication in each industry. In manufacturing, the design of the process by which the product will be manufactured and the design of the product itself overlap and are highly integrated (see Figure 1). Whereas in construction, the design of how the product will be built comes after the product has been designed. That is, in the construction industry, the design of the construction process is intimately related to fabrication of the components of the product, but completely separate from product design. This structure is significant when considering the timing with which process

technologies are considered. As illustrated in Figure 1, since the process design occurs after product design in construction, consideration of technologies used for the construction process occurs after product design. Effective consideration of automated construction technologies in the design of a project requires a re-structuring of the traditional project delivery process.

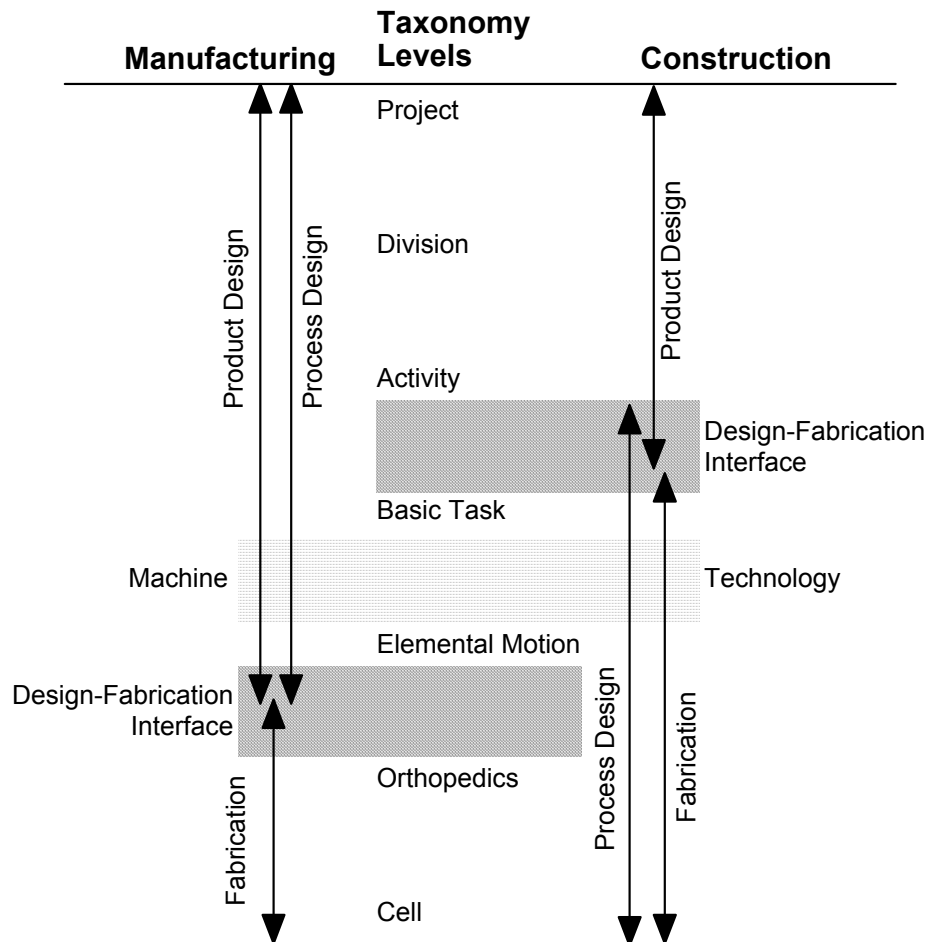


Figure 1. Design-Fabrication Interface, Manufacturing and Construction (Everett and Slocum, 1994)

Related CII Research

Past research studies undertaken by CII have addressed the issue of technology innovation and implementation in the construction industry. The CII Technology Survey Task Force was formed to identify innovations and emerging technologies that could lead to improvements in construction productivity (CII, 1994). The Task Force was successful in identifying over 300 technologies, which are housed in the Advanced Construction Technology Systems (ACTS) database. The ACTS database was designed to classify, document, and retrieve information about emerging construction technologies. This research led to the subsequent development of the Emerging Construction Technologies website (www.new-technologies.org/ECT/Index.html) which provides on-line access to the database and an opportunity for technology developers to showcase their products to the construction industry.

CII research has focused on the application of radio frequency identification (RFID) tagging (CII, 2001). The results of this research include lists of frequently asked questions and lessons learned related to RFID use. Additionally, a decision-support process chart was developed to facilitate selecting the appropriate type of RFID system to implement.

A recent CII study investigated pre-fabrication, pre-assembly, modularization, and offsite fabrication (PPMOF) in construction (CII, 2002a). CII Project Team 171 found that PPMOF offers a substantial opportunity to improve project performance and overcome external and internal project challenges. Successful implementation of PPMOF requires systematic analysis and decision-making. Key factors influencing the decision-making, including new technologies and a changing construction environment, have expanded and changed in the last decade. This increases the need for the structured decision-making process described in this guide. With this motivation, the CII research team extended prior research, identified state-of-the-art PPMOF

practices, and developed a decision framework to assist project teams in considering possible use of PPMOF. In developing the decision framework, the research team focused on identifying the requirements for effective use of PPMOF on industrial projects. The framework includes a decision timing map, tools for strategic analysis, and suggestions for tactical analysis in the PPMOF decision process. It also includes a spreadsheet-based Strategic Analysis tool to assist in the process. The tool and this document can be used separately, but they are intended to be used together.

CHAPTER 3

RESEARCH OBJECTIVES AND METHODOLOGY

The goal of this research study is to facilitate the advancement of automation in the construction industry. According to The American Heritage Dictionary (1983), *automation* is: 1) “the automatic operation or control of a process, machine, equipment, or system; 2) the mechanical and electronic techniques and equipment used to achieve automatic operation or control; and 3) the condition of being automatically controlled or operated. With this definition in mind, for the purposes of this study and within the context of the construction industry, the CII Project Team defined automation as:

“the use of mechanical and electronic means to achieve automatic operation or control to reduce potential exposure, time, or effort while maintaining or improving quality.”

Within the wide range of tools and equipment used in the construction industry, some can be considered automated and others not. It is clear that a bull float used for manually finishing concrete slabs is not an automated technology, while a remote controlled concrete finishing robot is considered an automated technology. For other mechanical or electronic tools, though, categorizing them as automated technologies is not so obvious. When a nail gun is used instead of a hammer to secure roof shingles with nails, for example, part of the task, namely the driving of the nail, is performed by mechanical means. There is more to the entire operation, however, than just driving the nail. The nail must be properly located and held upright. When using a nail

gun, the carpenter must locate the nail gun in the right spot, hold it upright and steady, and then squeeze the trigger to eject the nail. Direct human involvement in the sighting, control, and action of the tool remains. For this study, automated technologies were considered to be those that allow the worker to be removed from direct involvement at the work face. When using an automated technology, the worker is able to control and conduct the work from a distance, without direct connection to the operation. Technologies that do not meet this criterion, such as a nail gun, were not considered in this study.

Many aspects of the construction industry are automated. Automation is present in the design of the project, reproduction of contract documents, fabrication of materials and equipment, delivery of materials to the site, and placement, erection, and finishing activities on the site. The scope of the research study was limited to automation of the construction process. The study does not address automation of the design, operation, or maintenance of a project. Construction was intended to relate to the fabrication, placement, and erection of all materials and equipment on a project. Fabrication for projects is not limited to the jobsite. Therefore, offsite fabrication was also considered in the study. Additionally, the study considered the work conducted by a general contractor, subcontractor, fabricator, and any other entity involved in the construction of a project.

To facilitate the advancement of automation in the construction industry, this study focused on the design of the permanent features of the project, not the temporary processes and structures used to build the project. It was recognized that the design of the permanent features of a project influences the extent of automation during construction, and that the design of a project and the process used to create and communicate the design can be modified to enhance construction automation. Therefore, the study was aimed at investigating the relationship

between the design and construction automation. In general, designing for construction addresses the constructability of a project. In this respect, the study focused on the automation subset of a project's overall constructability, which can be referred to as "automation constructability". By addressing the constructability of a project from an automation viewpoint, it is anticipated that the designer can help place the constructor in a position to more fully automate the construction process.

With this research goal and context in mind, the CII Project Team established the following specific research objectives for the study:

- Identify barriers in the design and design process that limit or prohibit the use of automated technologies during construction.
- Develop and accumulate design phase practices that, when implemented, enhance the ability to automate construction activities. The practices are to reflect the capabilities and limitations of current automated technologies and the application of current design practices. No attempt was made to consider or predict the impacts of design on future automated technologies.
- Identify benefits to the project from the use of existing automated construction technologies and from the practice of designing for construction automation.
- Develop a resource for designers to assist with addressing construction automation in the design of a project. The resource was to provide designers with the ability to access and learn about design barriers that prohibit the use of construction automation and search for project-specific design practices to incorporate into their designs.

The research was expected to provide unique knowledge of the relationship between elements of design and the use of automation in construction work. It was anticipated that design for automation practices can be developed and barriers characterized through information gathered from automated equipment manufacturers, construction contractors, design professionals, fabricators, and personnel in other industries that have successfully integrated automation. The approach to the research study involved gathering and analyzing information from these sources as described in the five tasks below:

Task 1: Gather information on automated technologies used in construction

To determine how the design affects construction automation on a project, there must first be an understanding of the available automated technologies. The capabilities and characteristics of the technologies along with the limitations associated with their use must be understood. The objective of this task was to thoroughly understand existing technologies such that a relationship could be made to the design of a project.

Three separate efforts were undertaken as part of this task. The first activity was the collection of automated technology information from the manufacturers and suppliers of the technologies. Manufacturers and suppliers commonly provide technology information on their websites, in industry periodicals, and in marketing brochures. Keyword searches were conducted of the World Wide Web to generate a list of technologies that are currently available and under development. Construction industry periodicals (e.g., *Engineering News-Record*) were also reviewed to learn about available technologies. When available, additional information on the characteristics and performance of specific technologies was downloaded from the web or requested from the manufacturer for reference.

The second effort was a survey of construction firms regarding the list of automated technologies that was compiled. The intent of the survey was to draw out the extent to which the technologies are used in practice and whether further use is recommended. For prototype technologies still under development, an assessment of whether value was seen in their development was also desired. The sample used for the survey comprised of construction companies consisting of the top 400 contractors as ranked by *Engineering News-Record* (ENR), construction companies located in the Pacific Northwest, and CII member organizations. This sample was selected because it represents a broad distribution of construction firms with regards to size, type, location, and trade. The survey instrument was a written questionnaire mailed to the companies. The questionnaire included a list of the technologies collected as part of the initial activity of this task.

The last effort as part of this task was a review of construction industry periodicals and academic journals. An electronic, keyword search of article databases was conducted to locate articles that address the topic of automation in construction in general, and specifically designing for construction automation. The intent of this effort was to gain an understanding of the barriers and benefits of automation and potential design for automation practices from a source other than the construction firms. In addition, this search provided additional in-depth information about technology implementation and assessment, especially related to those technologies currently in the prototype stage.

Task 2: Survey constructors, designers, and fabricators regarding automated technology use

A second survey was conducted to gather in-depth knowledge from different perspectives in the construction industry about the use of the technologies in practice. The survey was

conducted through in-person interviews of contractors, designers, and fabricators. The interviews were standardized through a set of structured questions designed to uncover the reasons for using automated construction technologies, the barriers and benefits associated with the technologies, the productivity related to their use, and the design features and activities that facilitate their use.

The sample of contractors, designers, and fabricators used for the survey consisted of those located in the Pacific Northwest (Oregon and Washington) with which the researchers have working relationships. The sample of contractors also included those firms that responded to the survey in Task 1 and indicated that they were available for further contact regarding the study. For the contractor's perspective, interviews were conducted of both project managers and equipment operators. Careful considerations were made to obtain a range of construction companies, based on annual revenue, type of firm, and type of work performed. Design firms were selected based on the type of designs produced and firm size to ensure a wide representation of the industry. Employee count and annual revenue were used to determine their relative size. Fabricators were also interviewed to get another perspective concerning automation. Interviews with fabricators were based on the general categories of technologies used by constructors as determined from the list of technologies developed in Task 1, and on the potential for influence by the fabricator on the design. Personnel at each of the firms were contacted and asked to participate in the interview. When meeting the interviewee in person was not practical, the interview was conducted via telephone. Four separate questionnaires, one for the construction project managers, the equipment operators, the designers, and the fabricators, were created for use during the interviews.

Task 3: Survey other industries regarding their approach to designing for automation

The project team recognized that examples of successful implementation of automated technologies in the workplace exist outside of the construction industry. It was assumed that those industries that have fully integrated automated technologies into their production processes have made changes to the design of the products and the design effort to accommodate the technologies. In an attempt to learn from the successes and experiences of other industries, interviews of personnel in other industries were also conducted to gather information concerning how well other industries have come to include automated technologies. Industries considered for interview were those that design and produce products in an automated fashion, and whose products could be significantly impacted by the use of automation in the production process. Those selected for investigation were the computer/high-tech, shipbuilding, manufactured home, automotive, and airplane industries.

A list of targeted personnel in each of these industries was developed for interviews. The list was developed from a combination of personal contacts of the CII Project Team members and convenience based on locale. Because each of the industries is different, semi-structured in-person interviews were conducted without a formal questionnaire, but with a focus on gathering the same information related to barriers, benefits, and best practices associated with designing for automation that was collected in the constructor, designer, and fabricator interviews.

Task 4: Determine benefits from, and barriers to, designing for automation, and develop design practices that facilitate the use of automation during construction

The data collected from Tasks 1 through 3 was used as the basis for assessing the relationship between design and construction automation. An assessment of the extent to which

different types of technologies are currently used and their potential for future use was made based on the responses to the mailed technology survey. The assessment was made by simply counting the number of responses for each technology. A high number of responses was interpreted as indicating a positive response.

Assessments of the benefits and barriers of automating the construction process, and the best practices for designing for automation, were made from the in-person interviews and literature review. This data is primarily qualitative in nature. The interview responses to each question were grouped together according to discipline, i.e., the project manager responses were grouped together into one file, the equipment operator responses were grouped together in another file, and so forth. The CII Project Team then reviewed the data files and, utilizing its design and construction education and experience, identified trends and major themes in the responses. The knowledge obtained from the literature review was used to supplement the interview responses. Where applicable, the information collected from the interviews of personnel in other industries also guided the Project Team's analysis of the data.

Task 5: Develop a resource for the diffusion of the study findings to the construction industry

A task which the Project Team considered to be important for advancing the use of automated technologies in construction was that of making the study findings available to the construction industry. A website was selected as the means for diffusing the findings because it can be easily accessed and is commonly used. It was envisioned that designers would be able to access and learn about barriers that prohibit the use of construction automation and search for design practices to incorporate into their designs and design processes. In addition, the website could provide descriptions of available automated technologies and links to the manufacturers.

Study Investigators

The research study was conducted by a Project Team composed of both academics and industry professionals. The research activities were conducted primarily by researchers at Oregon State University with assistance from Purdue University. Advice and guidance on the study activities were provided by the industry professionals on the Project Team. A list of the Project Team members is provided in Appendix A.

CHAPTER 4

RESULTS

Beginning with the literature search, the study was undertaken as planned with each task completed successfully. The literature search uncovered an extensive amount of information on existing and prototype technologies that was used to supplement the industry surveys. Information related to designing for automated construction, however, was limited. Although a facility's design was commonly mentioned as a barrier to automating the construction process, further consideration and discussion of how the design affects automation and the design practices that facilitate automation were not addressed in significant depth. The results of the literature search are provided in the Literature Review section of this report. The results of the remaining study tasks are provided below.

Search for Automated Construction Technologies

The search for automated construction technologies exposed 87 different automated construction technologies that are currently in use or under development. The list of technologies along with a description of each is provided in Appendix B. To assist with the evaluation of the technologies and with communication of the technologies in the subsequent survey and interviews, the technologies were categorized according to the type of work performed: concrete and masonry construction, excavation and earthmoving, site inspection and surveying, painting and coatings, material and asset management, steel fabrication and erection, and finishing. These categories were selected because they reflect the common types of technologies available and the traditional breakdown of construction work on projects. The

percentage of automated technologies found in each of these categories is shown in Figure 2. Of the available technologies, most are designed for concrete and masonry construction (37%). Many technologies are also available for excavation and earthmoving operations (18%) and for applying paint and coatings (15%). It is interesting to note that current technologies primarily perform larger scale activities involving materials that are typically larger in size and weight (e.g., concrete, masonry, and steel). The exception to this is automated welding robots. Automation is also common for materials that are produced and available in modular units (e.g., masonry block and plywood sheets). Technologies are not currently available for activities that require extensive, intricate movements and precise manipulation and control of small parts and pieces in the field, such as for mechanical and electrical work.

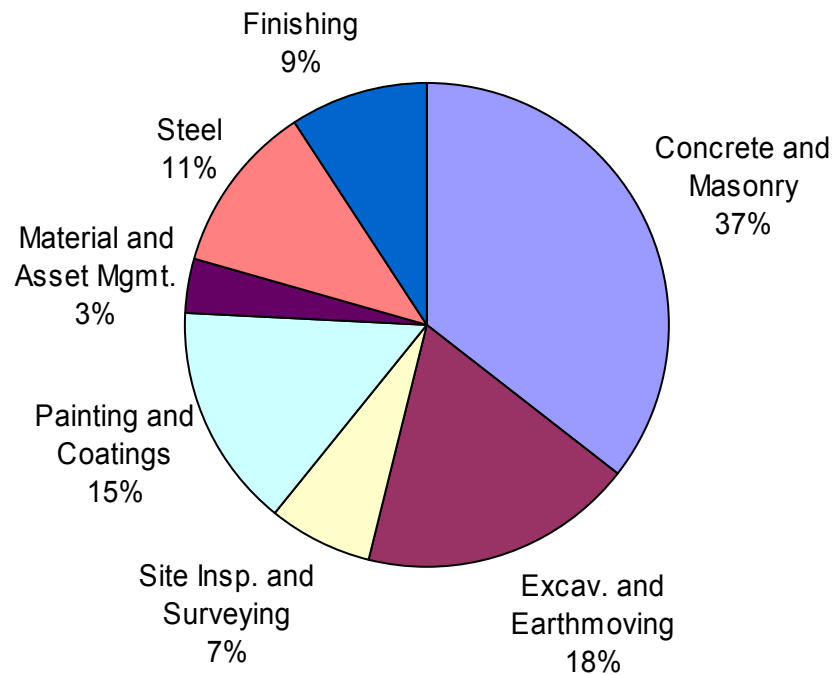


Figure 2. Type of Work Performed by Existing Automated Technologies

Survey of Constructors Regarding Automated Construction Technology Use

Following the search for available technologies, a survey of constructors was conducted regarding the extent of use of the technologies found in the search. The intent of the survey was to determine the level of application of the technologies in practice and their perceived value. A questionnaire was prepared that included the list of technologies (organized according to the categories mentioned previously) and noted whether the technologies were commercially available or currently prototypes under development. The questionnaire asked the constructors to respond to the following questions regarding each listed technology:

Which of the following automated construction technologies:

- a.) Does your firm utilize in its construction operations?
- b.) Has your firm considered, but not used?
- c.) Would you recommend for use by others?
- d.) Do you see value in this product's development?

The questionnaire was mailed to a total of 1,087 construction companies consisting of the top 400 contractors as ranked by *ENR*, construction companies located in the Pacific Northwest, and the CII member organizations that perform construction work. The survey sample included large and small companies involved in heavy civil, commercial, residential, and industrial related work. The sample was chosen based on convenience and to reach a wide range of companies based on type, size, and location. The large sample size also decreases the likelihood that none of the constructors are familiar with a particular technology. Copies of the survey cover letter and questionnaire are provided in Appendix C.

Of the 1,087 questionnaires distributed, 78 (7.2%) were completed and returned. The responses were tabulated for each technology (see Appendix D) and are summarized in Table 1. Table 1 describes those technologies that are predominantly used by construction companies and shows where value is seen in development. The survey revealed that there is a strong prevalence in concrete and masonry construction of automated mobile screeding, rebar bending, and concrete surface treatment. In addition, responses suggest that there is value in developing further technologies for automating reinforcing cage fabrication for beams and columns, and for mobile bricklaying. Excavation and demolition responses indicate that remote control soil compaction is used exceedingly more than other technologies within the category. Automated dump trucks and global positioning system (GPS) aided excavation appear to be highly considered applications for implementation, but with little or no actual implementation. One such implementation has proven to reduce cost by thirty percent through the use of automated trenching and pipe placement (Lee, et al., 1999).

The survey also reveals that automated technologies have not yet been greatly implemented for inspection and surveying activities except for a strong prevalence of robotic pipe inspection. For structural steel construction, metal welding and cutting systems are widely used and are recommended for use. Also, robotic welders are implemented extensively by many companies throughout the industry. Lastly, material and asset management technologies appear to have developmental value amongst industry members, especially real-time construction tracking systems.

Table 1. Technologies Predominantly Used and whose Development is Recommended

Response	Construction Category	Automated Technology
Technology Used	Concrete and Masonry	Horizontal concrete distributor Concrete surface treatment applicator Rebar bending machine Concrete screeding machine
	Excavation and Earthmoving	Remote controlled soil compactor Directional boring Earthmoving guidance system
	Site Inspection and Surveying	Robotic pipe inspection
	Painting and Coatings	Robotic paint removal
	Material and Asset Mgmt.	Real-time equipment tracking system Remote controlled forklift
	Steel	Robotic welding machine Automated cutting machine
	Finishing	Ceiling board manipulator Robotic glass handling machine
Value in Development	Concrete and Masonry	Robotic bricklaying machine Rebar cage fabricating machine Robotized spraying of GFRC panel
	Excavation and Earthmoving	Automated pipe laying Robotic drilling and cutting system Virtual reality Remote controlled heavy equipment
	Site Inspection and Surveying	Aerial bridge inspection
	Painting and Coatings	Automated finishing of tank surfaces Remote controlled paint removal
	Material and Asset Mgmt.	Real-time equipment tracking system
	Steel	Remote controlled pile driver
	Finishing	None

Construction Project Manager Interviews

The interviews of construction project managers focused on several topics related to designing for automation. A questionnaire was developed that asked the project manager about the extent of use of automated construction technologies, the reasons for their use, and the barriers and benefits of their use. Questions also solicited examples of how the design of projects and the design process could be modified to facilitate implementation of the

technologies. Copies of the cover letter and questionnaire are provided in Appendix E. The interviewees were also shown the list of 87 automated technologies for reference during the interview to familiarize themselves with the available technologies.

A total of 29 interviews of construction project managers were conducted. The personnel interviewed were employed in a wide range of types and sizes of firms with offices located in the Pacific Northwest. Careful consideration was made to select managers who work for a wide range of construction companies based on annual revenue (see Figure 3). The majority of firms earn between \$10 and \$20 million in annual revenue. The construction companies in which the project managers were employed are primarily general contractors (69%). The companies perform work in each sector of the construction industry: residential, industrial, commercial, and heavy civil. Care was also taken to ensure that interviews were conducted of project managers who work in a wide variety of types of firms. Figure 4 shows the work performed by the firms according to Standard Industrial Classification (SIC) codes. Residential and commercial building (SIC codes 152 and 154), and heavy construction (SIC codes 161 and 162) were most often listed as types of work performed.

In addition to making sure that a wide range of the industry was represented in the study, it was essential that the available automated technologies apply to those sectors of the industry that were actually surveyed. Without such overlap, a disconnect would exist between the knowledge source and the information in question. Figure 4 also shows the number of technologies on the list of available technologies that apply to each SIC code. It should be noted that a technology may apply to more than one SIC code. The figure illustrates that interviews were conducted in all SIC codes in which technologies are present, and multiple interviews were conducted within the SIC codes in which the most technologies are present. Therefore,

information was solicited from project managers who work in the sectors of the industry in which automated technologies are predominantly present.

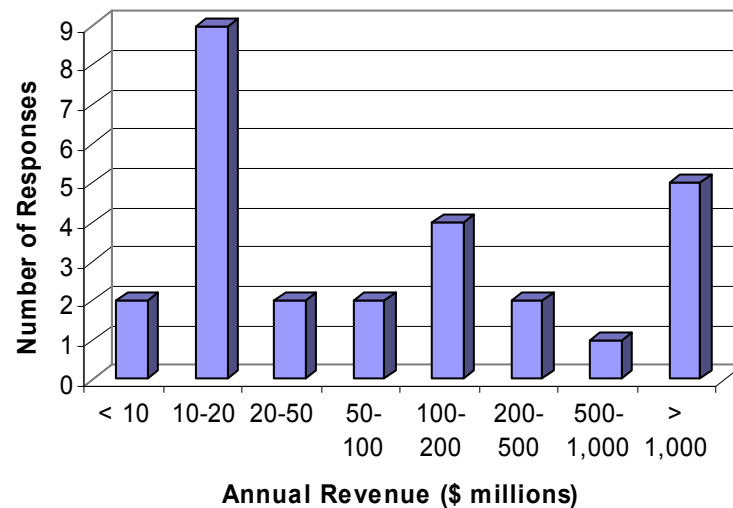


Figure 3. Size of Project Manager Firms Surveyed based on Annual Revenue

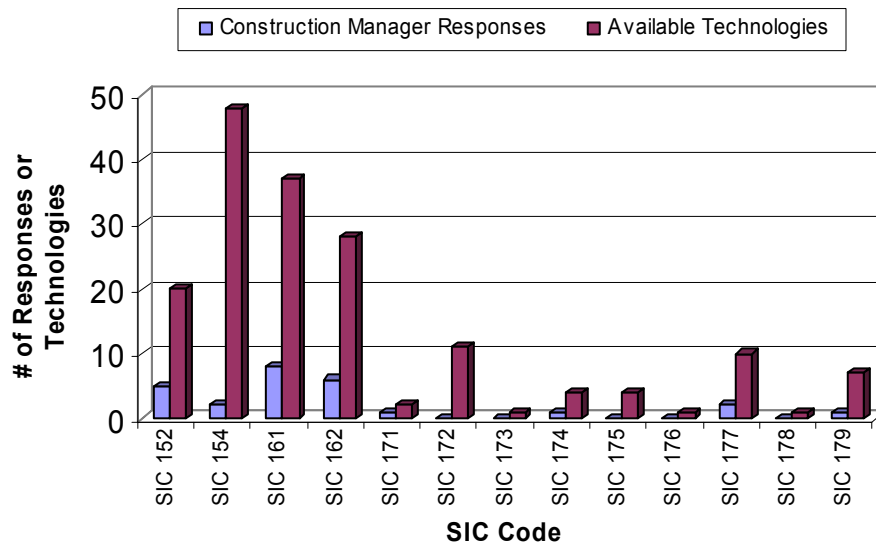


Figure 4. SIC Codes for Project Manager Firms Surveyed and Available Technologies
(Note: Of the 87 technologies found, many relate to more than one SIC code.)