AUTOMATION AND ROBOTICS OPPORTUNITIES: CONSTRUCTION VERSUS MANUFACTURING

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ABSTRACT: Automation and robots are frequently mentioned as solutions to industrywide problems of increasing costs, declining productivity, skilled-labor shortages, safety, and quality control. Despite numerous attempts to develop automation and robotics for construction field operations, few practical applications can be found on construction sites today. The promises of robotics remain unfulfilled, and attempts to transfer automation technology from manufacturing have not been optimal. Identification of opportunities for automation requires analysis of construction work at the appropriate level. This paper presents a hierarchical taxonomy that divides construction field operations into several levels. The basic-task level is the appropriate level for construction automation. The paper presents a set of basic tasks that describe construction field work. Construction is compared to highly repetitive manufacturing operations to gain insight into the relationships among product design, process design, and fabrication. In manufacturing, product and process design are closely interrelated. In construction, process design is completely separate from product design, but is intimately related to fabrication. Until construction product and process design become more highly integrated, automation must occur at the basic-task level. Advances in construction automation will continue to be characterized by a machine performing physically intensive basic tasks, operated by a human craftsperson performing the information-intensive basic tasks.

INTRODUCTION

Some construction processes lend themselves to automation. Others do not. For example, machines excel at physically intensive tasks that require speed, strength, repetitive motions, and operation in hostile environments. Humans are still more cost effective at information-intensive tasks that require judgment, sensing, and adaptability.

Automation and robots are frequently mentioned as solutions to perceived industrywide problems of increasing costs, declining productivity, skilled-labor shortages, safety, and quality control. Despite numerous attempts to develop highly automated machines and robotics for construction field operations, few practical applications can be found on construction sites today. This paper presents a model of how construction field operations are organized so that future work in construction automation and robotics will be more likely to succeed.

Any problem in construction requires analysis at the appropriate level of detail. For example, if the federal government decided to formulate a national industrial policy, it might compare the construction industry to the manufacturing industry, to the aerospace industry, or possibly to the construction industries of other countries. This analysis would be performed at the most general level. A scientist developing hearing protection devices for jackhammer operators might study cells of the inner ear. This investi-

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gation would be at a microscopic level. National industrial policies and hearing loss are both significant issues in construction, but they obviously require different levels of attention.

Identification of opportunities for automation and robotics in construction should also be given the appropriate level of attention. Given limited resources to research and develop new technologies, it is prudent to consider carefully which types of construction work should be automated before commencing research on any specific project. A small amount of effort spent up front identifying appropriate tasks will result in more efficient use of research budgets, and more successful deployment of new technology.

Several studies have attempted to identify which types of construction work are best suited to automation. Warszawski (1990) suggest that four generic or multipurpose robots could perform 10 "basic activities" (positioning, connecting, attaching, finishing, coating, concreting, building, inlaying, covering, and jointing) common in building work. Tucker (1988) computes the "automation potential" of 17 "distinct areas." Kangari and Halpin (1989) rank 33 "processes" according to need, technology, and economics, to arrive at a "robotics feasibility" score. Demsetz (1989) advocates a two-step approach, first identifying potential benefits of automation, then dividing the work between human and machine to optimize the contribution of each.

Alternatively, this paper presents a model of the organization of construction field operations. A hierarchical taxonomy of construction field operations divides construction work into several levels. Highly repetitive manufacturing operations are classified at a very fine level, but machines suitable for manufacturing automation cannot cope with the complexities of constantly changing construction sites. Machines designed to replace human craft workers approach construction work at too general a level. These machines are too complex, too expensive, and too unreliable to be practical. It will be shown that the appropriate level for construction automation technology is found between the level of highly automated manufacturing machines and the level of human craft workers.

The objective of the present paper is to offer an explanation of how construction field operations may be organized in the context of a hierarchical model. An improved understanding of the relationships between product design, process design, and fabrication in construction field work, and where their interfaces occur relative to available machine technology, leads to identification of the appropriate level for application of automation and robotics.

TAXONOMY OF CONSTRUCTION FIELD OPERATIONS

Construction field operations can be classified into a hierarchical taxonomy as shown in Table 1 (Everett 1990, 1991). Starting from the most general perspective, the construction project is divided into seven levels, each more detailed or refined than its predecessor.

Project

Construction differs from most other industries because of its "project" (level 1) orientation. "Projects are distinguished by their relatively short time frame; definite starting and stopping points; non-routine, often unique, interrelated activities; and a limited time, budget, and resource allocation for the projects performed" (Frankel 1990). Typical projects include petrochemical plants, office buildings, single family homes, and highways.

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TABLE 1. Taxonomy of Construction Field Operations

Level (1)	Description (2)	Examples (3)
1	Project	Petrochemical plant, office building
2	Division	Concrete, masonry, mechanical
3	Activity	Drywall partition, concrete wall
4	Basic Task	Connect, cut, measure, position
5	Elemental Motion	Reach, grasp, eye travel
6	Orthopedics	Muscle, bone, joint
7	Cell	Muscle fiber, nerve

Division

Level 2 represents a breakdown of on-site construction work into the major "divisions" of work or trades. The most commonly used classifications in the United States are the 16 Construction Specifications Institute (CSI) divisions, such as concrete, masonry, mechanical, and electrical work (CSI 1988).

Activity

Level 3 breaks divisions into specific units of work, or "activities." Using the CSI format, an activity corresponds to a specification subsection. An activity represents all the field work that results in a recognizable, completed unit of work with spatial limits and/or dimensions. Examples include, "build an 8-in. (20-cm) block south foundation wall" or "erect structural steel at third floor."

Basic Task

Level 4, "basic tasks," will be discussed in detail later in the present paper.

Elemental Motion

Level 5 examines elemental motions. Industrial engineers have been studying manufacturing work at the elemental motion level for nearly a century. In 1903, Frederick W. Taylor divided shoveling work into several simple motions in a series of time studies (Taylor 1947). In the 1920s, Gilbreth and Gilbreth developed time and motion studies by dividing human movements into 17 components called "therbligs" such as reach, grasp, and eye travel (Gilbreth and Gilbreth 1977). Another example of the elemental motion level is methods-time measurement (MTM) (Maynard et al. 1948). MTM classifies human movements into a set of motions similar to therbligs but also applies standard units of time to each motion to arrive at the total theoretical time required to perform a given task using a prescribed method. Both therbligs and MTM are still widely used in manufacturing.

Orthopedics

At the "orthopedics" level (level 6), physicians and physiologists analyze human motions by studying muscles, bones, joints, and the nervous system. Researchers in the fields of ergonomics and occupational biomechanics examine work at this level to optimize safety and efficiency of the human machine (e.g. Chaffin and Andersson 1991).

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Cell

At the "cell" level (level 7), investigators examine individual muscle fibers, nerves, and cellular metabolic activity to understand how the human machine functions and how certain occupational injuries and illnesses are caused.

All of the levels in the taxonomy have been thoroughly described and catalogued with the exception of the basic-task level. This forgotten level turns out to be the critical level for construction automation.

Basic tasks are the fundamental building blocks of construction field work, each representing one in a series of steps that comprise an activity. Any productive work performed in the field can be categorized into one or more basic tasks. Table 2 presents a set of 12 basic tasks with definitions and examples. The 12 basic tasks are: connect, cover, cut, dig, finish, inspect, measure, place, plan, position, spray, and spread (Everett 1991). Some of these basic tasks are adapted from Warszawski and Sangrey (1985). All basic tasks can be performed by human craftspeople; some can be performed by machines. Other investigators have described some components of construction work at a level analogous to basic tasks (Halpin and Woodhead 1976; Warszawski 1990; and Tucker 1990).

PHYSICAL AND INFORMATION COMPONENTS OF WORK

Every construction chore has physical components and information components (Porter and Millar 1985). To complete the chore, some combination of human and machine must be able to execute all of the physical and all of the information components. Table 3 presents a system for classifying construction equipment into four categories: tools, power tools, automatic tools, and robots, based on the distribution of physical components and information components between man and machine.

TABLE 2. Basic Tasks

Basic task (1)	Definition (2)	Examples (3)
Connect	Join or attach components together	Screw, nail, bolt, staple, weld
Cover	Spread or overlay sheet material over surface	Unroll carpet or single ply roofing
Cut	Penetrate or separate with sharp edge	Saw wood, cut drywall, drill hole
Dig	Loosen, remove, or move soil	Excavate trench, backfill
Finish	Apply continuous mechanical treatment	Grind, bushhammer, sand, rub
Inspect	Examine critically to identify flaws or verify correctness	Read level, verify alignment of machinery
Measure	Determine or lay out dimensions	Mark drywall, lay out track
Place	Move small object to specified location and orientation	Set tile, lay brick, align conduit
Plan	Gather information, think about upcoming work	Read blueprints, formulate work sequence
Position	Move large object to specified location and orientation	Erect steel beam, lift drywall
Spray	Direct jet of liquid or particles, no contact with surface	Spray paint, sandblast
Spread	Distribute liquid or paste material	Paint with brush, cast concrete

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TABLE 3. Distribution of Physical and Information Components of Work

Hardware (1)	Physical input (2)	Information input (3)	Examples (4)
Tool	Human	Human	Hammer, screwdriver
Power tool	Machine/human	Human	Jackhammer, electric drill
Automatic tool	Machine/human	Human/machine	Automatic transmission
Robot	Machine	Machine	SSR-3

Tools are implements that convert forces and energy into useful work. When using a tool, the human craftsperson supplies all of the physical input and all of the information input, the tool only redirects the human's effort. Examples are the hammer, screwdriver, brace and bit, block and tackle, and shovel.

Power tools supply some or most of the physical component of the work. A human operator still supplies some of the physical input by guiding, supporting, or pushing the power tool. The human operator supplies all of the information input by deciding when and where to start and stop, how fast to proceed, or how hard to push. Small examples include electric drills, jackhammers, and nail guns. Larger examples include earth moving equipment and cranes, although some components of these may better fit the next category.

Automatic tools supply some or most of the physical input, and also some of the information processing components of the work. A human operator is still necessary to control or guide the automatic tool. Examples include automatic transmissions in earth moving equipment, laser guided graders and dozers, screw guns with clutches, load monitors on cranes, and pressure regulators on compressors. All of these automatic tools have some type of self regulating feedback mechanism that relieves the human operator of some decision making duties.

Robots supply all of the physical input and all of the information input to the work. Some human information input or programming may be necessary, but the robot generally makes its own decisions and executes the work independently. Scores of prototype robots have been developed over the past decade, but few practical examples can be found on construction sites today (Normile 1993). One well publicized example is Fireproofing Spraying Robot (SSR-3) of Shimizu Corp., Tokyo.

The distribution of the physical and information components of work in construction field operations is quite different from that in highly repetitive manufacturing operations. Too often in the past, construction automation and robotics researchers have approached the development of construction technologies from a manufacturing perspective.

MANUFACTURING VERSUS CONSTRUCTION

Historically, efforts to study highly repetitive manufacturing work have approached the work at the elemental motion level. Industrial engineers developed MTM and therbligs to optimize the duration and efficiency of repetitive human motions. Elemental motions are characteristic of highly repetitive mass production assembly operations, where workers typically sit or stand in a fixed position and the work comes to the worker. Through elemental motion analysis, industrial engineers attempt to simplify the work so the human worker can perform with little information input and minimal

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wasted physical input. Most of the information components of the work are embodied in the process design, so neither human nor machine need make decisions. In these types of manufacturing operations, the "largest common denominator" is a cycle of elemental motions.

Many parts of construction work are repetitive, but the cycles are much more complex than in mass production manufacturing. While each construction work cycle may be similar to its predecessor and successor, the cycles are not identical. In construction, the craftsperson typically must plan and lay out the work, gather appropriate tools and materials, and move his/her body throughout the work area, while performing the work. Construction craft workers continuously provide information input by adapting to the changing geography of the workplace, to changes in the positions of their bodies relative to the work, and to minor differences between successive repetitions of the work.

From an industrial engineers' perspective, construction work varies so much from cycle to cycle that elemental motions cannot be considered the largest common denominator. Construction work is characterized by cycles of more general basic tasks. For example, hanging drywall is considered repetitive. The craftsperson must measure the wall and lay out the cuts (measure), cut the drywall panel (cut), lift the panel into place (position), and screw or nail the panel to the studs (connect). The cycle of measure, cut, position, and connect repeats over and over; however, the basic task steps in one cycle are different than their counterparts in other cycles.

Manufacturing and construction exhibit fundamental differences in the relationships among product design, process design, and fabrication. Product design determines what the final constructed facility or manufactured item will look like and how it will perform in service. Process design determines how the product will be built. Fabrication is the actual building or manufacturing of the product.

The traditional model in manufacturing is the waterfall model, where product design is handed to process designers who then determine the manufacturing process. Product design and process design occur sequentially, but both cover similar ranges of levels in the hierarchy down to the elemental motion level.

The new production philosophy, known by names such as lean production, world-class manufacturing, concurrent engineering, and others has its roots in Japan in the 1950s (Womack et al. 1990; Koskela 1992). The new production philosophy emphasizes, among other things, coordination or integration of product design and process design. Designers of the final product help determine the processes to be used to create the product, and process designers contribute to the final product design. The new production philosophy has already revolutionized automobile manufacturing and electronics, and is the emerging mainstream approach in other industries as well (Koskela 1992).

Manufacturing product designers and process designers generally work for the same firm. Whether working sequentially in the traditional model or working in parallel in the new production philosophy, product and process designers control the work all the way down to the elemental motion level. Labor controls the fabrication part of the work up to the orthopedics level. Labor can dictate how hard it will work or possibly how fast it will move, but the shop floor workers follow carefully choreographed routines.

The left side of Fig. 1 graphically depicts product design and process design interfacing with fabrication somewhere between the elemental mo-

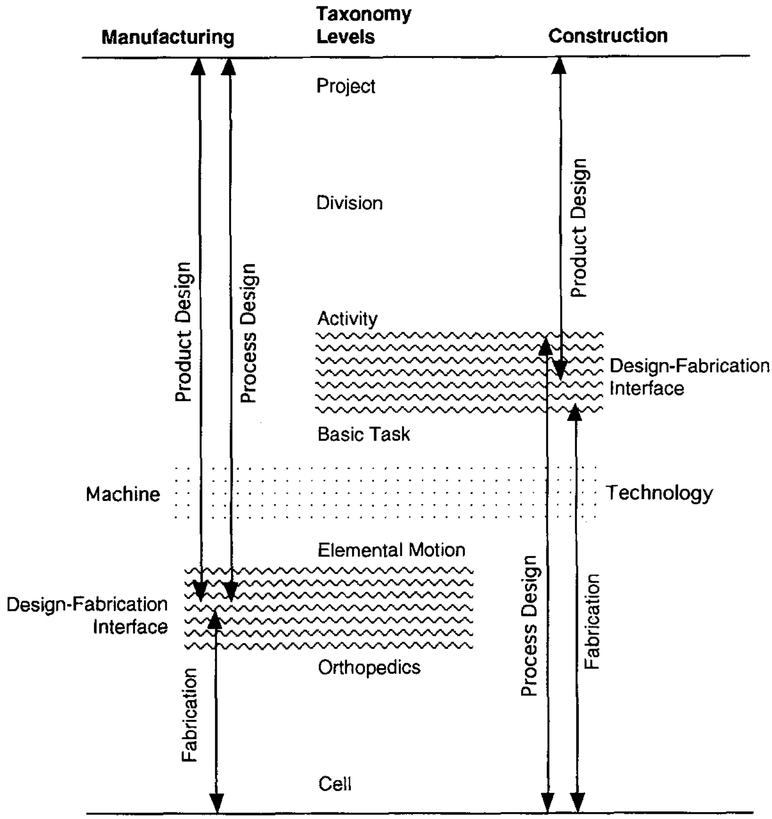

FIG. 1. Design-Fabrication Interface, Manufacturing and Construction

tion and the orthopedics levels. The interface level is shown as a wide wavy band rather than a thin straight line to emphasize that the level may not be obvious or constant.

The rapidly growing fields of ergonomics and occupational biomechanics may foretell a movement to push product and process design down even further, to include the orthopedics level as well.

In construction, product design and process design are relatively independent of each other, although the interface between them is not necessarily a crisp line. Some product designs are more detailed or more complete than others. A construction process planner, possibly an estimator, may be required to complete the architect's product design as part of the construction process design. With so-called performance specifications, the process designers and fabricators may have significant input into product design. For example, an architect's product design may specify a two hour fire wall. The contractor's process design could select a number of materials or technologies such as drywall on steel studs or masonry construction. Constructability reviews incorporate constructor input into product design to improve practicality and cost effectiveness of major product design decisions, but they seldom affect the details of how the work will be performed in the field.

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Product design is performed by architects and engineers who design the constructed facility down to about the activity level, but who do not get involved in the building process other than inspecting the finished work for conformance to their specifications. Constructors have control over process design and fabrication but generally have little or no input into product design.

Normally, a distinct separation exists between the product designers and the process designers. In construction, the product designers and process designers are usually separate organizations with different, often conflicting, objectives.

In construction, process design and fabrication are closely linked. Craft workers contribute to process design and perform the work. They do not just execute the work, they also help decide what to do, how to do it, when to do it, and where to do it. There are, of course, limits. Product design, construction technologies, materials, and equipment constrain process design and fabrication options, but to a large extent, craft workers provide both physical and information input to the work.

The right side of Fig. 1 shows construction process design and fabrication occurring nearly in parallel, both interfacing with product design somewhere between the activity and the basic-task levels. Again, the interfaces and overlaps are shown in a range because the level at which the interfaces occur and the degree of overlap of process design and fabrication with product design varies from project to project.

For example, the product design may specify an activity such as construct an 8-in. (20-cm) concrete block wall. The contractor completes the product design with exact locations and dimensions. The superintendent and mason establish the process design and perform the fabrication by controlling basic tasks such as which blocks to lay in which order (measure, spread mortar, position or place block), how many courses to complete before raising the staging (plan and position), how often to check for plumbness and alignment (inspect), when to tool the joints (inspect and finish), etc.

IMPLICATIONS FOR AUTOMATION IN CONSTRUCTION

Significant improvements in production have been achieved by substituting machines for human workers in many types of manufacturing work. Machines are capable of performing elemental motions that do not require thinking or adaptation to minor changes. The shaded bar in Fig. 1 shows the state of the art in machine technology occurring between the basic task and elemental motion levels. Current machine technology is well above the design-fabrication interface in manufacturing, so application of automation and robotics in manufacturing can occur relatively easily and effectively. Manufacturing product and process designers design and control the work down to a level where today's machines can take over fabrication, possibly replacing human workers.

For better or for worse, the culture of the construction industry has evolved quite differently. Product designers design only down to the activity level. There has been no historical need or incentive for architects and engineers to concern themselves with the intricacies of the work in the field, so finer levels of detail have not been incorporated into design. While this industry characteristic has its advantages, it poses a major problem for developing automation and robotics technology for construction field operations. There is a substantial gap between the finest level of product design detail and the most general level of machine technology.

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The gap occurs at the basic-task level. Today's machines are capable of performing physically intensive basic tasks such as connect, dig, finish, position, and spray but have trouble with information-intensive basic tasks such as inspect, measure, and plan. Virtually all construction activities require performance of some information-intensive basic tasks, so very few practical examples of construction robotics or highly automated machines have been developed. Virtually all successful advances in construction automation have been devices that perform one basic task and are controlled by a human operator who guides the machine and decides when and where to start, and when and where to stop. Examples abound of machines that connect, cover, cut, dig, finish, place, position, spray, and spread, all single basic tasks.

CONCLUSION

In the context of a hierarchical taxonomy, this paper has presented the relationships among product design, process design, and fabrication in construction and manufacturing. The two industries are dramatically different. In the foreseeable future, it is unlikely that construction product designers and process designers will coordinate their efforts to the extent common in manufacturing.

Approaches to automation in manufacturing cannot be transferred to construction, instead construction must develop its own strategies. With the current organization of the construction industry, and state of the art in machine technology, advances in automation of field operations will continue to occur at the basic-task level.

Machines excel at physically intensive basic tasks that require speed, strength, repetitive motions, and operation in hostile environments. Human craft workers are still more productive and cost effective than machines and computers for the information-intensive basic tasks.

Automatic machines that can perform one physically intensive basic task, operated by a human craftsperson who performs the information-intensive basic tasks, are technically and economically feasible today. By properly distributing the physical and information components of construction work between man and machine, problems of increasing costs, declining productivity, skilled-labor shortages, safety, and quality control can be solved.

FUTURE RESEARCH

To make construction robotics and automation feasible at the activity level, the gap between construction product design and machine technology must be closed. This can happen in two ways: by extending design detail to the level where a machine can be told exactly what to do, or by improving the information processing capabilities of machines so they can figure out what to do. Fortunately, the gap is narrowing from both directions. Advances in computer aided design may one day allow the same computer that stores the product design to control a robot or machine that can perform the fabrication. Technological improvements in sensors, controls, and actuators may allow smart machines and tools to continuously report their progress and location to the central computer. With continuous updating of work completed, the ever changing project site geography can be incorporated into the instructions given to the fabrication machines.

The automated building construction systems developed by several large Japanese contractors (Skibniewski and Wooldridge 1992; Normile 1993) are

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examples of attempts to make construction product and process design parallel and move the design-fabrication interface further down the hierarchy. When the computer storing the product design and the machine performing the fabrication can communicate effectively, product design, process design, and fabrication can become integrated. When that happens, highly automated machines and robots will become feasible and practical.

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