Automation and Robotics in Construction X
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Design-Fabrication Interface: Construction vs. Manufacturing

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Abstract

Fundamental cultural differences between industries helps explain why automation and robotics have been successful in manufacturing but have largely failed in construction. In construction there has traditionally been a clear separation between a project's design phase and its field operations. In manufacturing, engineering design and shop floor fabrication are highly integrated.

This paper examines the differences between construction and manufacturing in the context of hierarchical structures. Each industry is divided into hierarchical levels including, in order of increasing level of detail: Project, Division, Activity, Basic Task, Elemental Motion, and Orthopedics. In construction, the design-fabrication interface occurs between the Activity and Basic Task levels. Architect/engineers, the product designers prepare plans and specifications at the Activity level of detail and turn them over to field personnel, the process designers who organize and perform the work from the Basic Task level down. In manufacturing, the design-fabrication interface occurs much lower in the hierarchy, between the Elemental Motion and Orthopedic levels. Product and process designers collectively decide not only what the finished product will look like, but how the product will be manufactured, step-by-step. The shop floor worker provides physical input, but little organizational input for the work.

Researchers should formulate their strategies for introducing automation and robotics in construction field operations recognizing the differences between construction and manufacturing. Automation techniques which have succeeded in manufacturing cannot be forced upon the construction industry in its current organizational structure. It will be far easier for construction automation researchers to develop rational strategies than to alter the organization of the construction industry.

INTRODUCTION

Any problem in construction requires examination of the industry 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 of detail. A scientist developing hearing protection devices for jackhammer operators might study cells of the inner ear. This investigation would be at a microscopic level of detail. National industrial policies and hearing loss are both significant issues in construction, but they obviously require different kinds of attention.

An earlier paper presented a taxonomy of the construction industry, shown in Table 1 (Everett 1990). Starting from the most general perspective, the industry is broken down into nine levels, each an order of magnitude more detailed than its predecessor.

Table 1.
Taxonomy of the Construction Industry

Level	Examples
1. Industry	Construction, manufacturing
2. Sector	Building, industrial, heavy
3. Project	Office building, power plant
4. Division	Concrete, electrical, mechanical
5. Activity	Drywall partition, HVAC duct
6. Basic Task	Position, Connect, Measure
7. Elemental Motion	Reach, grasp, eye travel
8. Orthopedics	Muscle, bone, joint
9. Cell	Muscle fiber, nerve

Level 1 is the entire construction *Industry*. The construction industry can be compared to other industries such as manufacturing, aerospace, mining, or agriculture. The construction industry can be divided into *Sectors* (Level 2) representing fundamentally different types of constructed facilities such as general building, heavy construction, and special trades.

Construction differs from most other industries because of its *Project* (Level 3) 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.

Level 4 represents a breakdown of on-site construction work into the major *Divisions* of work or trades. The most commonly used classifications in the U.S. are the sixteen Construction Specifications Institute (CSI) divisions, such as concrete, masonry, mechanical, and electrical work (CSI 1988). Level 5 breaks Divisions into specific units of work, or *Activities*. Using the CSI Format, an Activity would correspond to a specification subsection. An Activity represents all the field work which results in a recognizable, completed unit of work. Examples include install drywall partition, install HVAC duct, and erect steel column.

Level 6 is *Basic Tasks*. Basic Tasks are the fundamental building blocks of construction field work, each representing one in a series of steps which comprise an Activity. Any productive work performed in the field can be categorized into one or more Basic Tasks. The set of Basic Tasks is mutually exclusive and collectively exhaustive for all on-site construction work. Basic Tasks can be performed by human craftsmen, machines, or both. The Basic Tasks are: Connect, Cover, Dig, Finish, Inspect, Measure, Place, Plan, Position, Spray, and Spread (Everett 1991).

Construction can be divided into still finer levels of detail. Level 7 examines *Elemental Motions*. Industrial engineers have been studying manufacturing work at the Elemental Motion level of detail for nearly a century. In 1903, Frederick W. Taylor, the Father of Scientific Management, divided shoveling into several simple motions for his time studies (Taylor 1947). In 1920's, Frank and Lillian Gilbreth developed time and motion studies by dividing human movements into seventeen components called *therbligs* (backwards spelling of Gilbreth, almost), such as reach, grasp, and eye travel (Gilbreth and Gilbreth 1924). Another example of Elemental Motions 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.

At the *Orthopedics* level (Level 8), physicians and physiologists analyze human motions by studying muscles, joints, and nerves. Ergonomics and occupational biomechanics examine work at this level of detail to optimize safety and efficiency of the human machine. At the *Cell* level (Level 9), investigators examine individual muscle fibers, nerves, and cellular metabolic activity to understand how the human machine functions and how occupational injuries and illnesses are caused.

The objective of this paper is to describe at which levels in the taxonomy the interface between design and fabrication occurs for construction and for repetitive manufacturing operations. Too often in the past, construction automation and robotics researchers have approached the development of construction technologies from a manufacturing perspective. An understanding of the differences between construction and manufacturing will help future researchers develop more realistic strategies for construction automation.

MANUFACTURING LEVELS VS. CONSTRUCTION LEVELS

Industrial Engineers have been able to analyze manufacturing work down to the Elemental Motion level of detail for two major reasons. First, the repetitive nature of many types of manufacturing work allows consistent detailed analysis. Second, the design and engineering of the manufactured product are intimately connected to the manufacturing process.

Repetitive Motions

Historically, efforts to study manufacturing work have approached the work at the Elemental Motion level of detail. Industrial engineers developed MTM and therbligs to optimize the time and efficiency of repetitive human motions. The motions described by MTM and therbligs are characteristic of mass production assembly lines, 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 minimal amounts of thinking and/or wasted movement. In highly repetitive manufacturing operations, the "largest common denominator" is the Elemental Motion cycle.

Many parts of construction work are repetitive, but the cycle is 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 layout the work, gather appropriate tools and materials, move his/her body to a new location, and then perform the work. Construction craft workers continuously adapt to the changing geography of the workplace, changes in the positions of their bodies relative to the work, and 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. One must move up to the Basic Task level in the Taxonomy of the Construction Industry to reach the fundamental unit of work.

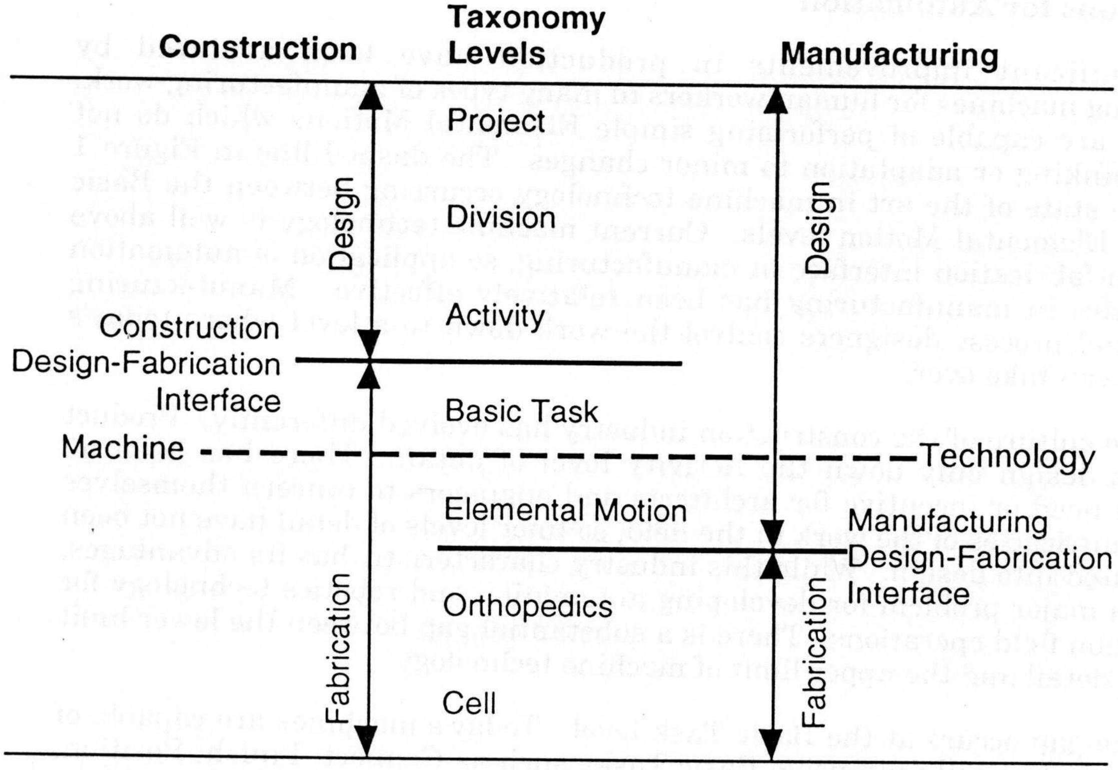
Products and Processes: the Design-Fabrication Interface

Construction and manufacturing exhibit fundamental differences in where the interface or transition occurs between product design and process design or fabrication. Manufacturing product design is closely related to process design. The designers of the final product have a great deal of control over the processes used to create the product and process designers help determine the final product design. Much of Industrial Engineering is dedicated to improving manufacturing processes and the relationship between product and process. Typically, the product designers and the process designers work for the same manufacturing firm.

In repetitive manufacturing operations, the product-process design team controls products and processes all the way down to the Elemental Motion level of detail. 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 right side of Figure 1 graphically depicts the design-fabrication interface occurring between the Elemental Motion and the Orthopedics levels of detail. The rapidly growing field of occupational ergonomics may represent an effort to push process design down even further, to include the Orthopedics level as well.

Figure 1

Design-Fabrication Interfaces for Construction and Manufacturing



In construction, there is little overlap between product design and process design or fabrication. Architect/engineers control product design down to the Activity level, but do not get involved in the building process other than to inspect the finished work for conformance to design specifications. Constructors control the fabrication process design but generally have little or no input into product design. 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. A distinct separation exists between the product designers or architect/engineers, and the process designers or craft workers. In construction, the product designers and process designers are almost always separate organizations with different, often conflicting, objectives.

In construction, the product designers control the work only down to the Activity level of detail. The fabricators or craft workers determine how the work will be performed all the way up to the Basic Task level. The left side of Figure 1 shows the design-fabrication interface for construction occurring between the Activity and the Basic Task levels. For example, the product design may specify where an Activity such as an eight inch concrete block wall is to be built, but the mason controls Basic Tasks such as which blocks to lay in which order, how many courses to lay before raising the staging, how often to check for plumbness and alignment, when to tool the joints, etc.

Implications for Automation

Significant improvements in production have been achieved by substituting machines for human workers in many types of manufacturing work. Machines are capable of performing simple Elemental Motions which do not require thinking or adaptation to minor changes. The dashed line in Figure 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 has been relatively effective. Manufacturing product and process designers control the work down to a level where today's machines can take over.

The culture of the construction industry has evolved differently. Product designers design only down the Activity level of detail. 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 lower limit of design detail and the upper limit of machine technology.

The gap occurs at the Basic Task level. Today's machines are capable of performing physically intensive Basic Tasks such as Connect, 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 information intensive Basic Tasks, so very few practical examples of construction robotics or highly automated machines have been developed. The successful advances in construction automation have almost always been machines that perform one Basic Task and are controlled by a human operator who decides when and where to start, and when and where to stop. Examples abound of machines which connect, cover, dig, finish, place, position, spray, and spread, all single Basic Tasks.

In order to make construction robotics and automation feasible, the gap between design and machine technology must be closed. This can happen in two ways: by increasing the level of design detail or by improving the information processing capabilities of machines. Fortunately, the gap is narrowing from both directions. Advances in computed aided design may one day allow the same computer which stores all the product design details to control a robot or machine that performs 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.

Until the product design and process design are integrated, it will be extremely difficult to develop practical fully automated construction machines.

Human operators are still more productive and cost effective than machines and computers for the information intensive Basic Tasks.

CONCLUSION

This paper has shown where the design-fabrication interface occurs in the context of a Taxonomy of the Construction Industry for construction and manufacturing. In manufacturing, product design and process design are closely interrelated. The interface between design and fabrication occurs at a fine level of detail in the taxonomy. Machines can perform many repetitive manufacturing operations because the state of the art of machine technology is above the level of the design-fabrication interface.

In construction, product design and process design are distinct from each other and the interface between them occurs at a high level of detail in the taxonomy. Current machine technology is below the construction design-fabrication interface, and machines cannot perform all of the steps necessary to be fully automated.

Until the gap between construction product design and technology of the machines that perform the fabrication is closed, the promises of practical robotics and highly automated machines will remain unfulfilled. Successful advances in construction automation will continue to be developed at the Basic Task level.

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