BACK TO BASICS IN CONSTRUCTION AUTOMATION

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ABSTRACT

One strategy to improve construction productivity and safety is to develop and use automation. This paper proposes a rational and systematic methodology for selecting construction work suitable for automation. The United States construction industry is organized into several levels. Short term efforts to introduce automation should be applied to the "Basic Task" level. Prioritization of Basic Tasks for further R&D should consider competing technologies and labor acceptance.

1. INTRODUCTION

Engineers and scientists constantly strive to find better ways to perform old chores. The steady decline of productivity in the United States construction industry offers many challenges and opportunities to those leading the industry into the future. One strategy to improve construction productivity, as well as safety and quality, is to develop and use automation.

2. AUTOMATION

One characteristic which separates humans from other animals is the development and use of tools and machines. Construction field work is a combination of inputs from humans and machines, ranging from solely human input or manual labor at one extreme, to all machines or robots at the other. See Figure 1, adapted from Tucker [1]. To "automate" construction work is to increase the contribution of machines or tools while decreasing the human input. Increasing automation represents a shift toward robots (to the right in Figure 1).

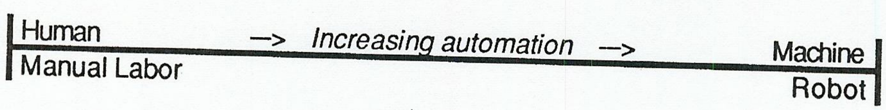

Figure 1. Automation Spectrum.

3. LEVELS

Any problem in construction requires examination of the industry at an appropriate level of detail. For example, if the federal government were to formulate a national industrial policy, it might compare the construction industry to the manufacturing industry. A physician studying work related hearing loss might investigate individual cells in the human body. This paper organizes the construction industry into nine levels, each an order of magnitude more detailed than the previous level. See Table 1.

Level	Examples
1. Industry	Construction, manufacturing
2. Sector	Building, power, heavy
3. Project	Field work, A/E, management
4. Division	Concrete, electrical, mechanical
5. Activity	Concrete wall, slab on deck
6. Basic Task	Position, connect, measure
7. Elemental motion	Reach, grasp, eye travel
8. Orthopedics	Muscle, bone, joint
9. Cell	Muscle fiber, nerve

Table 1. Levels of the construction industry.

4. TASK SELECTION

Given limited resources to research and develop innovative tools and machines, it is prudent to consider carefully which construction work should be automated before commencing research on any specific project. A small amount of money and effort spent up front identifying appropriate tasks will result in more efficient use of a research budget, and more successful deployment of new technology.

Five recent studies have attempted to identify which types of construction work are best suited to automation. Warszawski and Sangrey [2] suggest that four generic or multipurpose robots could perform ten "basic activities" (positioning, connecting, attaching, finishing, coating, concreting, building, inlaying, covering, and jointing) common to much building work. Alonso Holtorf [3] ranks commercial building subsystems, analogous to Divisions (Level 4), based on "physical susceptibility" to arrive at an "automation susceptibility index".

Tucker [1] computes the "automation potential" of seventeen "distinct areas", equivalent to Divisions (Level 4) or Activities (Level 5), as the product of "cost percentage" and an inefficiency rating. Kangari and Halpin [4] rank each of thirty-three processes, ranging from Divisions (Level 4) to Basic Tasks (Level 6), according to need, technology, and economics, to arrive at a "robotics feasibility" score. Demsetz [5] advocates a two step approach, first identifying potential benefits of automation, then dividing the work between man and machine to optimize the contribution of each.

5. SELECTING APPROPRIATE LEVEL FOR AUTOMATION

The entire construction industry cannot be automated immediately, and many parts will never be. In deciding where to introduce automation, various investigators have looked at levels ranging from detailed Elemental Motions (Level 7) all the way to entire Divisions (Level 4).

For nearly a century, industrial engineers have examined manufacturing assembly line labor at the Elemental Motion level (Level 7). One widely used system, Methods-Time Measurement (MTM) [6], focuses on human motions such as reach, move, and turn. Industrial engineering can also be applied to construction. If the goal is to replace manual human labor with machines, it may be productive to understand the Elemental Motions (Level 7) of humans.

Some investigators propose robots which perform Activities (Level 5) or entire Divisions (Level 4), but this author suggests they are aiming at too high a level for short term practicality. Automation is most reliable and cost effective, and produces the highest quality for simple, repetitive tasks which require little judgement. Automating entire sets of actions found in Level 4 or Level 5 requires one machine to perform complicated series of tasks which vary greatly in their degree of complexity, repetitiveness, and need for human intervention.

The experiences of the automobile industry should serve as a lesson to construction. In attempting to switch from assembly lines all the way to factories full of robots, some U. S. automobile manufacturers found that the robot technology was not as well developed as expected, and that management was not prepared to deal with the technological changes. The construction industry would do well to avoid the same costly mistakes.

Widespread use of robots or highly automated machines would require a complete restructuring of the construction industry. Changes would be needed in design, project management, materials, processes, and the makeup of the labor force. Large capital investment would be required. In an industry as fragmented as construction, these issues would be at least as important as the technical problems of developing functional robots.

In between the detailed Elemental Motions of Level 7 and the broad Activities or Divisions of Levels 5 or 4, are the Basic Tasks of Level 6. Table 3 introduces and defines a set of Basic Tasks from which all construction work can be composed. The eighteen Basic Tasks are adapted and significantly expanded from Warszawski and Sangrey's ten "basic activities" [2] mentioned in Part 4. Basic Tasks may be performed by humans as well as robots.

Basic Task	Definition	Examples
Cast	Pour concrete into forms or slabs	Cast slabs, columns, beams
Caulk	Extrude sealant between adjacent objects	Seal precast concrete joints
Clean	Remove unwanted dirt or impurities	Sweep floor, scrape forms
Coat	Spread layer of liquid or semiliquid on surface	Paint with brush, plaster, glue
Connect	Join or fasten two objects to each other	Nail, bolt, screw, weld, tape
Cover	Spread or unroll sheet material on surface	Unroll carpet, insulation
Cut	Divide one piece into two or more; remove excess material	Saw wood, cut drywall
Finish	Apply continuous mechanical treatment to surface	Sand, grind, rub concrete
Inlay	Set small flat pieces next to each other	Set tile, wood flooring
Inspect	Examine critically to detect flaws or verify correctness	Visually check finishes
Lay	Set blocks next to or on top of each other	Lay bricks, CMU, masonry
Measure	Determine or layout correct dimensions	Mark drywall, layout track
Place	Move small object to correct location and orientation	Install hangers, light fixtures
Position	Move large object to correct location and orientation	Erect steel beams
Prepare	Make material ready for further use	Mix paint, unpack boxes
Pull	Draw electrical wire through conduit	Pull cable
Spray	Direct jet of liquid or particles, no contact with surface	Spray paint, sandblast
Think	Form ideas, gather information, plan upcoming work	Read plans, ask questions

Table 2. Basic Tasks

There are few economically successful uses of robots in construction, but in manufacturing, robots and highly automated machines perform Basic Tasks such as painting (Spraying) and welding (Connecting) very effectively. Other manufacturing robots perform assembly operations similar to Elemental Motions. The simpler the work, the easier it is to automate.

Examples of successful Basic Task automation in construction abound: Pneumatic nail guns (Connecting), electric saws (Cutting), cranes (Positioning), and power floats for concrete (Finishing). Even with these machines, construction work is still very labor intensive. Currently, construction automation is near the left or manual labor end of the Automation Spectrum of Figure 1, and at the Basic Task level (Level 6) of Table 1.

Deployment of robots and highly automated machines to perform entire Activities (Level 5) or Divisions (Level 4) would shift construction practice to the right on the Automation Spectrum, as well as up one or more levels on Table 1. The experience of other industries suggests that increased automation works better for simpler work, not more complex work. Successes in construction automation will continue to be found at low levels.

6. BASIC TASK EXAMPLES

Table 3A lists, in sequential order, many different components of Concrete Wall construction, along with corresponding Basic Tasks. Table 3B shows the same components and Basic Tasks as Table 3A but is sorted alphabetically by Basic Task.

Activity - Concrete Walls	Basic Task
read plans	Think
layout forms	Measure
measure forms 1st side	Measure
position forms 1st side	Position
connect forms 1st side	Connect
position rebar	Position
tie rebar	Connect
insert blockouts	Place
connect blockouts	Connect
inspect rebar	Inspect
insert form ties	Place
measure forms 2nd side	Measure
position forms 2nd side	Position
connect forms 2nd side	Connect
connect form ties	Connect
inspect forms	Inspect
cast concrete	Cast
apply curing compound	Coat
disconnect forms	Connect
strip forms	Position
clean forms	Clean
apply curing compound	Coat
rub walls	Finish

Table 3A. Concrete Wall components in sequential order

Activity - Concrete Walls	Basic Task
cast concrete	Cast
clean forms	Clean
apply curing compound	Coat
apply curing compound	Coat
connect forms 1st side	Connect
tie rebar	Connect
connect blockouts	Connect
connect forms 2nd side	Connect
connect form ties	Connect
disconnect forms	Connect
rub walls	Finish
inspect rebar	Inspect
inspect forms	Inspect
read plans	Think
layout forms	Measure
measure forms 1st side	Measure
measure forms 2nd side	Measure
insert blockouts	Place
insert form ties	Place
position forms 1st side	Position
position rebar	Position
position forms 2nd side	Position
strip forms	Position

Table 3B. Concrete Wall components sorted by Basic Task

Table 4 presents a matrix with Activities (Level 5) in the columns and Basic Tasks (Level 6) forming the rows. The first Activity column, Concrete Walls, is identical to Table 3B. Another example Activity, Interior Partitions, is included to show that other Activities can be broken down and grouped into the same set of Basic Tasks. The matrix could be expanded to include any number of Activities in additional columns. Eighteen rows, one for each Basic Tasks listed in Table 2, would include all possible components of construction field work. Table 4 shows only the eleven Basic Tasks associated with the example Activities.

Basic Task (Level 6)	Activity (Level 5)	
	Concrete Walls	Drywall Partitions
Cast	cast concrete	
Clean	clean forms	sweep floor cleanup
Coat	apply curing compound apply curing compound	tape joints - 1st coat tape joints - 2nd coat tape joints - 3rd coat
Connect	connect forms 1st side tie rebar connect blockouts connect forms 2nd side connect ties disconnect forms	connect track/header connect studs screw drywall connect corner beads
Cut		cut track/header cut studs cut drywall cut corner beads
Finish	rub walls	sand joints - 1st coat sand joints - 2nd coat sand joints - 3rd coat
Inspect	inspect rebar inspect forms	inspect joints
Measure	layout forms measure forms 1st side measure forms 2nd side	layout track/header measure track/header layout studs measure studs measure wall layout drywall measure corner beads
Place	insert blockouts insert form ties	align track/header align studs place corner beads
Position	position forms 1st side position rebar position forms 2nd side strip forms	position drywall
Think	read plans	read plans

Table 4. Matrix of Activities and Basic Tasks

Unless fundamental changes are made in processes and materials, robots must emulate human craftsmen and follow the same chronological sequences as their human counterparts. To automate an entire Activity, the robot must be capable of performing all the Basic Tasks in one column of the matrix. Some Basic Tasks may be difficult to automate, resulting in a complex and expensive robot. The potential advantages of the robot, such as improved Positioning or better Connecting, may be lost because the machine is much less efficient than a human at other Basic Tasks such as Thinking or Measuring.

After breaking construction field work down to the Basic Task level, one can ask which Basic Tasks are most suitable for automation. Technology which automates one Basic Task could be applied horizontally across the matrix to parts of many different Activities. For example, Connecting technology developed to improve productivity in

Concrete Walls may have applications in other Activities such as Interior Partitions. Rather than comparing the automation potential of Concrete Walls to Interior Partitions, one would now compare, for example, the automation potential of Measuring to Positioning. In other words, one should examine the rows, rather than the columns of the matrix in Table 4.

7. PRIORITIZING BASIC TASKS FOR AUTOMATION RESEARCH

Some Basic Tasks lend themselves to automation, while others do not. Machines are good at tasks requiring speed, strength, and repeatability. Humans are still more cost effective than machines at performing tasks requiring sensing, intelligence and adaptability. Efficient and logical use of scarce R&D funds requires that Basic Tasks be prioritized according to some criteria, so that the largest productivity gains are realized for the money invested.

Traditionally, business decisions to invest in new technology are based on economic and technical feasibility. Need based feasibility is also considered by Kangari and Halpin [4]. This paper recommends that prioritization of automation efforts, whether at the Basic Task level or other levels, also consider competing technologies and labor acceptance.

8. COMPETING TECHNOLOGIES

A competing technology may make automation less likely to succeed. For example, there will have been little point in developing an automated welding (Connecting) machine if welding becomes obsolete due to the invention of new adhesives. On the other hand, a competing technology may make automation more practical. For example, a different type of structural wall system, such as concrete blocks instead of cast-in-place concrete, may be more easily automated [8].

9. LABOR ACCEPTANCE

Modern management techniques stress involvement of the craftsmen in decision making. These craftsmen know the details of the work and have the most at stake in any attempts to change the work. Previous task identification work has included industry input by consulting with owners, contractors, robot manufacturers, and accountants. This is a top-down approach. The implication is that management will decide what should be automated, and then impose the new automation technology on labor, whether labor likes it or not.

Labor input is critical because:

- Labor knows details of the work better than management or academia. Labor can offer valuable opinions about what is needed, what works, and what does not.
- Labor will ultimately determine which new technology is adopted. Technical data and economic forecasts mean nothing if labor refuses to operate and maintain the new machines, for whatever reason.
- The U. S. construction industry appears to be in no hurry to fund automation research. Most funding will continue to come from the federal government. If and when labor perceives that automation reduces labor requirements by eliminating or de-skilling jobs, labor will use its considerable political power to steer funding toward research more in its interest.

Lane Kirkland [7], president of the AFL-CIO, and thereby head of all the U. S. building trades unions, said, "So long as the quest for improved productivity is perceived as either a device to make workers toil harder and longer or simply a means for higher profit, then workers will resist".

Before proceeding with automation research, it seems sensible to at least find out what labor thinks. Labor may not support the elimination or de-skilling of jobs, but probably will favor technology which increases safety and reduces heavy lifting, boring or dirty work. Labor, management, and government have many mutual interests. All can work together to promote automation.

For example, automation which increases safety has economic and social benefits for management and personal job satisfaction benefits for labor. Craftsmen's job satisfaction is very subjective, but it has direct and indirect effects on the bottom line. Low satisfaction leads to increased absenteeism, increased turnover, additional training for replacements, alcohol and drug abuse, increased accident rates, and low productivity.

Impending labor shortages can be lessened by allowing humans to continue to perform tasks at which humans excel, and letting machines perform the work machines do well. Management benefits when labor spends a larger fraction of its time in productive work. Labor also benefits. New, smarter tools require additional training and skills. By being more highly trained and more productive, labor may have a legitimate claim for higher wages.

Rather than resisting automation as a managerial plot to eliminate and de-skill jobs, labor is likely to embrace automation which not only preserves jobs, but increases job quality, skills and wages.

CONCLUSION

In order to improve construction safety and productivity through automation, this paper has:

- Divided the construction industry into several levels.
- Proposed that automation should occur at the Basic Task level.
- Defined a set of eighteen Basic Tasks from which all construction work is composed.
- Proposed that competing technologies and labor acceptance be considered when prioritizing automation R&D efforts.

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