# Feasibility and Implementation of Automation and Robotics in Canadian Building Construction Operations

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## Abstract

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Construction automation has received considerable attention in recent years as a means of countering the problems of declining productivity, increasing labour and safety costs, and labour scarcity. Although considerable attention has been focussed on hardware and software developments and on prioritizing research efforts, relatively little attention has been paid to the efficient implementation of automated and robotic equipment by contractors. This thesis addresses the feasibility of automation and robotics in Canadian building construction operations and identifies how implementation can be accomplished so that contractors can gain immediate benefits.

A methodology for analyzing the implementation of automation in construction operations is developed, based on the concept that manual, semi-automated, and fully automated tasks must be combined to achieve overall operation objectives. The construction of concrete slabs on grade is selected as a case study operation, considering semi-automated concrete placing and robotic floor finishing implemented separately or jointly. Information on local practices relating to manual and semi-automated work is obtained through structured interviews with five specialized contractors and observation of their crews. Information on robotic finishing is obtained through published reports and discussions with Japanese contractors.

The study highlights the importance of considering the entire operation when analyzing the implementation of automated equipment. Although automation can help achieve positive results by improving productivity, it may not always reduce manpower requirements and may afford quality improvements which do not always yield direct benefits. This suggests that careful planning is required to ensure that unrealistic expectations do not yield unexpected results.

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# CHAPTER I

# INTRODUCTION

Construction is one of mankind's oldest and most challenging activities. Today, many construction workers use skills and know-how that go back thousands of years. Most are skilled tradesmen who, like the craftsman and masterbuilder of the past, have learned their trade by example and site demonstration. Much of the industry's present craft-oriented structure has roots that go back to the medieval guilds of masons, carpenters, and smiths. Yet virtually each trade has had to adapt to the use of new materials and equipment, as the limits set by existing technology were slowly but progressively advanced. Today, while not yet a high-tech industry, construction is becoming increasingly technologically progressive.

Consider the evolutionary developments that have occurred in construction technology over the past 50 years. First, *mechanization* brought raw power to virtually every operation, from material handling to hand sawing. The potential must have seemed enormous considering that one gallon of gas, used in an engine of average efficiency, could do the work of about 90 men for one hour (Landels 1978). Second, *prefabrication* of structural and architectural components enabled the application of factory-based mass production techniques, thus further reducing labour requirements. Today, for example, the construction of a new single family house is estimated to require the assembly of over 3000 factory-made components ("New Homes" 1993). Third, development of *new materials* made it easier and less costly to build. The use of plastic pipes for example, is estimated to have reduced labour content in plumbing by about 25% (Zanasi 1983).

Fourth, and most recently, advances in *microelectronics* have enabled microprocessor control of construction equipment, computer-aided design and project management, and have opened the door to on-site automation and robotics.

Since the early eighties, over a dozen countries have undertaken research in on-site construction automation, much of it concerned with the application of robots and robotic technologies. The field is rapidly developing, both through short-term efforts aimed at improving current equipment and methods and through long-term research aimed at developing new construction paradigms. In Canada, in spite of the fact that construction automation was deemed to be a vital issue for the next decade in a survey of contractors (Revay and Ass. 1988), commitment to research and development (R&D) in the field of construction automation to date has been very limited. The fact that Canada has developed an excellent R&D base in industrial automation and robotics (Logie 1989), indicates that the country is technologically well equipped to support applications relating to construction. However, a commitment to research is required in the field of construction engineering and management in order to successfully bring automation to the Canadian contractor.

This thesis recognizes the potential that automation and robotics holds in helping the Canadian construction industry meet its changing needs, and represents one of the first attempts at analyzing the feasibility and implementation of possible applications. In the remainder of this chapter, the need for automation in the Canadian construction industry is first examined, and comparisons with the manufacturing industry provide valuable insight. The scope and objectives of the thesis are then defined, terminology is clarified, and the rest of the work is outlined.

## 1.1 Automation and the Canadian Construction Industry

Construction is Canada's largest industry, typically accounting for approximately 14% of the Gross Domestic Product (GDP) and employing approximately 6% of the available workforce (Rakhra 1988). By international standards, this represents a larger share of the national economy than in any other industrialized country except Japan (Glegg 1988). The industry holds a key role in economic development as it is closely linked to other sectors of the economy through the purchase of its inputs and through the use of its outputs: it has been estimated for example, that every dollar spent on construction in Canada adds about $ 1.83 to the economy (Rakhra 1988).

The construction industry faces many new challenges resulting from combined economic and technological forces. Many of these challenges are examined in this section and are found to be at least as strong motivators for applying automation in construction as they were in manufacturing. The industry, however, presents serious barriers which will influence when and how implementation will take place. These barriers are also briefly discussed.

### 1.1.1 Motivating Factors for Automation and Robotics in Construction

1. The need for productivity growth:

Although definitions and measurement of construction productivity may vary, most estimates point to a slow growth rate ("Canada Constructs" 1984; "Industry Profile" 1990), or even a decline when compared to other sectors in Canada (Rakhra 1988; Revay and Ass. 1988). However defined, the general consensus is that its improvement is a major area of concern. The issue is a serious one, because it is to the extent that the industry's productivity increases that it can absorb rising material, equipment, and labour costs without also raising prices, and thus remain both nationally and internationally competitive.

Historically in Canada, labour costs have risen faster than other costs of construction, except land ("Towards" 1973; Viau and Filion 1993). In addition, construction pays relatively high wages when compared to the rest of the economy, and particularly when compared to manufacturing (Viau and Filion 1993). Since construction is more labour intensive than manufacturing -labour typically represents 30-40% of costs in construction ("Construction" 1986) compared to 15-20% in manufacturing (Gold 1982)- its competitiveness is particularly influenced by the productivity of its labour.

During the seventies, when the manufacturing industry experienced conditions similar to these just described, i.e. poor productivity and rising labour costs, it realized that it could significantly increase its performance through the use of new automation technologies, particularly robots. In fact, productivity improvement/reduction of labour costs was found to be the most important reason for introducing robots in both Canadian (Hamidi-Noori and Templer 1983) and American (Ayres and Miller 1983) manufacturing firms.

By this standard alone, construction is also in need of such labour saving technology. To date, in fact, technology has been the most important factor contributing to construction productivity improvements (Adrian 1987; "Towards" 1973), responsible for as much as 70% of increases according to one study (Rakhra 1988). The manufacturing productivity increases resulting from the implementation of automation and robotics have been well documented (Ayres and Miller 1983; Meyer 1988), and research suggests that the use of similar technologies in construction could have a considerable positive impact on the industry's productivity (Moselhi and Hason 1989; Warszawski 1984).

2. The need to overcome shortages of skilled labour:

The construction industry's trade papers bear frequent witness to local labour shortages ("Shortage" 1988; "Construction Trades" 1989). Many reports also voice concern over future labour supplies, warning of 'critical shortages' for the 1990's ("May Be" 1988; "Skill" 1989), or even a 'worker-supply crisis' by the year 2000 ("Industry Faces" 1989). The situation is exacerbated by changing labour force demographics which will adversely affect certain provinces, most notably Ontario, where half the skilled labor force is expected to retire within the next ten years (Leslie 1988), and Québec, where aging of the construction labour force is recognized to be responsible for productivity losses and increasingly frequent labour shortages (Létourneau 1990).

While other industries, such as manufacturing, forestry, and mining, also face the problems of an aging labour force, the problem is more serious in construction because the entry of young workers in apprenticeship programs is declining much more rapidly: at the root of this problem is the declining attractiveness of construction work and the perception of better economic opportunities elsewhere ("Apprenticeships" 1989). Overcoming the shortages of skilled labour which affect the construction industry is considered to be a critical benefit of automation and robotics, although it was not found to be a prime motivator for manufacturing industries (Ayres and Miller 1983; Hamidi-Noori and Templer 1983).

3. The need for improved safety:

The potential for improving job safety is perhaps the most intuitively appealing aspect of automation and robotics, particularly in construction, which is still, by any standard, a high-risk occupation. In Canada, the industry has more than double the average national accident rate, making it second only to the forestry industry ("Les Accidents" 1987). Construction workers are also at risk from a number of occupational diseases caused by chemical pollutants, harmful construction materials, and physical stressors, such as noise, vibration, and radiation (Englund 1981).

In addition to the human cost, the high-risk nature of construction has substantial economic consequences. It has been estimated that direct costs, which include workmen's compensation premiums and the cost of compliance with safety regulations, and indirect costs, which include delays of work, negative impact on productivity, and low worker morale, amount on average to 4.8% of total project costs in the province of Quebec (Martel 1987).

4. The need for improved quality:

Over the past 10 years, the prime concern of most North-American, European, and Japanese manufacturers has been the ability to produce high quality products (Ayres et al. 1985). In this regard, the use of robots is widely recognized to be particularly successful (Ayres and Miller 1983; Gold 1983; Hamidi-Noori and Templer 1983). Recognizing the need to maintain its competitive strength, the government of Québec's has recently made 'Total Quality' a major priority of its industrial policy for the construction sector (Fontaine 1993).

In buildings, the consequences of poor quality can lead to rework during construction, repair during occupancy, and may result in failure at any time. In residential construction it has been suggested that 'doing it right the first time' could save $8,000 to $10,000 per house ("To Keep" 1986). In the Province of Québec, it has been estimated that failure to conform to specified levels of quality on the first try can represent up to 35% of contractors' business volume (Carrier 1991). Eventually, the use of automation and robotics may be particularly beneficial on smaller construction projects, which far outnumber larger projects, and are often plagued by less experienced personnel, and more frequent performance problems (Bartholomew 1987). It is expected that the potential reduction of direct manual labour through automation can significantly contribute to consistent improvements in quality.

5. The need to remain competitive:

Studies on technological innovation suggest that once developed, the rate at which an industry will adopt a new technology largely determines its competitive strength (Gold 1983). In Canada, the construction industry is thought to lag behind counterparts in other countries, particularly in the application of computer-based technologies ("Industry Profile" 1990). In the province of Quebec, the possibility of foreign involvement in the domestic construction market was identified as a major concern by a recent survey of industry practitioners (Théoret 1989). Since foreign contractors are increasingly using advanced technologies as the basis for competition (Halpin 1988; Hansen and Tatum 1989), adoption of similar technologies by domestic contractors is of prime importance in maintaining, and certainly in expanding, both domestic and international markets.

### 1.1.2 Barriers to Automation and Robotics in Construction

1. Technological constraints:

Automation and robotics technology has reached a stage of development which supports new applications in non-industrial environments (Sistler 1987; Stauffer 1987), of which construction is but one possibility. Foremost among the challenges facing the application of automation in construction is overcoming the complexity of the working environment. Unlike many manufacturing applications, the working environment in construction is largely unstructured and dynamic: work is custom built with little standardization of output, actual dimensions of components and their locations often vary from those specified on drawings, and few processes are routinely carried out at a single location.

Operating in such an environment suggests the need for sophisticated mobility, sensor, and control systems, with the added seemingly paradoxical requirement that the equipment need also be rugged, in view of the difficulties associated with outdoor work, dusty and cluttered spaces, and generally abusive manhandling.

2. Functional fragmentation:

In North America, the building delivery process is both vertically fragmented (between project phases i.e., planning, design, construction) and horizontally fragmented (between specialists in a given project phase), often by contractual obligation. While this fragmentation gives the industry much of the flexibility required to operate cost-effectively, it does not foster the kind of cooperation between designer(s) and contractor(s) required to develop new designs and implement new technologies.

By contrast, European and Japanese designers and contractors have a closer relationship than they do in North America, and even tend to share the risk on certain projects ("Japanese Bring" 1988; Howard et al. 1989). When making proposals, for example, European designers must specify the method of construction (Halpin 1988). In Japan, most large contractors are design-build organizations supporting in-house R&D departments. By concentrating all the skills necessary in one company, equipment and techniques which have been developed in-house are incorporated early on in the planning, followed through to the design, and are ultimately used in the execution of the project; site experience is then fed back into the design process, initiating advancements through more research.

The interaction between the product being designed and the processes required to create it is generally recognized as the most important element for automation to occur beyond the level of the independent machine performing an isolated task (Gold 1982; Hansen and Tatum 1989). In construction, the implementation of automation beyond that level will require changes in building design, construction, and management for which some degree of vertical and horizontal integration is a prerequisite.

3. Technology delivery and transfer:

If one defines a high-technology industry by the proportion of its output re-invested in R&D, construction would be at the bottom of the list. The level of construction R&D in Canada varies between 0.1 and 0.2 per cent of industry output: this represents 5 to 10 times less than what is invested by other sectors of the Canadian economy (Glegg 1988).

Additionally, due to the industry's fragmentation, construction R&D is conducted over an informal network of equipment and material suppliers, universities, and government institutions.

These factors pose a significant barrier because construction automation research can be costly and lengthy. It has been suggested, for example, that the minimum system engineering cost associated with the development of single-purpose construction robots is approximately 8 to 10 times greater than the cost of robot hardware and application software combined (Skibniewski 1985). Additionally, the level of investment typically required for commercialization of a product in construction far exceeds that required to produce the research results (Clark 1988).

4. Institutional constraints:

Implementation of automation may be significantly affected by the heavily institutionalized regulatory and industrial relations systems in construction. Industry practitioners are subjected to perhaps more regulations, administered by more levels of government, than those in any other industry. This regulatory framework hampers the industry's ability to innovate and prevents it from using, within a reasonable amount of time, the most technically advanced systems and materials because the proscriptive nature of building codes encourages only traditional building techniques (Clark 1988; Legget et al. 1968).

The construction industry is also unique in its industrial relations system, differing from the standard industrial relations system of other industries which is characterized by single union certification and single employer bargaining (Adams 1989). In most provinces today, multi-employer associations negotiate on a province-wide basis with single trade or multi-trade union organizations. In Quebec, a unique situation in North-America exists, whereas all workers must belong to one of five trade unions, all employers must belong to a provincial employer association, and settlements are extended by government decree over the whole province. The main effects of the decree system have been identified by a government study on deregulation as 1) restricting access of skilled workers and 2) impeding technological change ("Règlementer" 1989).

5. Business constraints:

The different nature of the construction market and the ensuing risks to construction firms make implementation of automation in construction more difficult than in manufacturing. For instance, in 1985, 90% of the 110,000 Canadian construction firms had 20 employees or less, and 95% had annual operating revenues of less than $1M (Glegg 1988). In Quebec in 1990, nearly 80% of construction employers had total wage disbursements of $100,000 or less ("Analyse" 1990). Another key feature of construction contractors is a high degree of leverage resulting from short term debt as the main source of financing for both operating capital and equipment purchases: in fact liabilities due to short term debt represent a larger proportion in construction than in manufacturing ("Towards" 1973). Construction is a also notoriously unstable, exhibiting both cyclical and seasonal instabilities: when both are combined, year to year employment is four times as unstable as in manufacturing ("Towards" 1973).

The portrait of the average Canadian construction firm which is obtained is one of a small, competitive, and highly leveraged firm, operating in a seasonal and cyclical industry, which due to functionally segregated delivery and production systems, is highly specialized and has short term, project specific needs. This type of environment makes any capital investment risky. The economic factors affecting the introduction of new technology in construction were perhaps best described almost twenty years ago by Legget et al. (1968), who wrote:

> A proposed innovation which shows the promise of reducing costs without any sacrifice in the other directions is almost certain to find acceptance. The main obstacle to rapid acceptance will be uncertainty that the cost savings will actually result or that there will be no sacrifice in performance or quality. Correspondingly, a proposed innovation which offers an increase in performance or quality at no extra cost will usually also find acceptance.

In the present context, this statement can be complemented by the following, from Ruberg and Sandberg (1987):

> Those (technological innovations) whose primary justification is quality improvement without increase in productivity need to overcome inherent disincentives in the building delivery process.

### 1.2 The Manufacturing Experience

Until the introduction of the first industrial robot 30 years ago, automation has been more or less synonymous with mechanization, as epitomized by serial production systems which require special purpose equipment and fixed transfer lines, resulting in mass-production and little flexibility. The landscape of modern manufacturing now consists of flexible manufacturing systems (FMS), composed of numerically controlled machines and robots integrated with one or several functions such as cost control and accounting, engineering and design, planning and scheduling, and storage and retrieval. While at this stage no single company, even in Japan, has been able to fully integrate all aspect of manufacturing, the evolution towards Computer Integrated Manufacturing (CIM) is well under way (Gold 1982). The experience gained by manufacturing industries since the introduction of robotics provides valuable lessons for construction.

The development of industrial automation since the introduction of robotics has occurred in three stages: clear need, rapid growth, and reassessment followed by sustained growth. During the first stage which began in 1961 with the installation of the first commercial industrial robot, the use of robots was constrained by their limited capabilities, the low wages rates of the time, and the perceived risks of a new and unproven technology (Meystel 1988). Since early robots did not necessarily perform their tasks more economically than human operators, justification for their use was found only in cases of clear need, i.e., in simple but hazardous applications.

The second stage dates back to the introduction of the first microcomputer controlled robot in the mid-1970's and was characterized by rapid implementation made possible by advances in technology, and fueled by decreasing productivity/increasing wage rates ("Industrial Robots" 1986). The use of robots during this period grew largely on the strength of simple applications, 80% of which included machine loading, spot welding, and spray painting ("Industrial Robots" 1986). In these cases, the robot was installed with minimum modifications to the existing process, usually limited to the direct environment of its application, and was mostly used as a direct replacement for a human operator, capable of working with the traditional low-cost or easily-manufactured components usually manipulated by hand.

The third stage of industrial robot development began in 1986 with a significant decline in robot implementation as manufacturers expanded the range of applications of robots and quickly became disappointed with their performance (Logie 1989; Taylor 1989). It is now recognized that the failure to consider the robot in a systems-oriented approach, especially in 'second generation' applications such as arc welding or assembly, resulted in many robots being either misapplied or improperly supported ("Industrial Robots" 1986; Logic 1989). Unlike most simple first generation applications, second generation applications require some level of integration between design and production. Successful second generation applications have, in fact, shown that the benefits of rationalizing the manufacturing process far outweigh the labour savings obtained through the immediate use of the robot alone (Ayres et al. 1985; Gold 1982)

While the effects of automation and robotics will not be mirrored exactly the same way in the environment of the construction industry, it is not unreasonable to assume that the evolution of automation in construction could follow the same path as in manufacturing. Thus, moving from the current stage of construction automation to a change in the way buildings are designed and constructed could take at least the same amount of time that it took to move from the first industrial robot to the integrated manufacturing systems of today; i.e. approximately 25 years.

The general lesson learned from manufacturing is that while automation of certain activities is successful only if significant changes in organization, design, and production are made, other activities can be successfully automated by integrating advanced equipment, with existing equipment and human workers. It is precisely such activities which, if automated, could enable Canadian contractors to realize immediate benefits and could provide them with a competitive edge.

## 1.3 Scope And Objectives

The field of construction automation has been rapidly developing over the past ten years. The Canadian construction industry must carefully consider automation and robotics technologies in order to meet its changing needs. This research will show that although considerable effort has been focussed on hardware and software developments for construction applications, with a particular emphasis on robotics, and on the identification of which activities should be automated, relatively little attention has been paid to the concerns faced by the eventual end users of the technology, i.e., how would contractors implement automation.

The motivation for this research comes, therefore, from the fact that a commitment is required not only to develop construction automation technologies but also to bring these technologies to contractors. Such a commitment is seen to be particularly relevant, at this time, to the needs of the Canadian construction industry, since it would:

1. allow Canadian contractors to gain immediate benefits from currently available or soon-to-be-developed technologies,
2. foster the development of construction automation experience which, in turn, could lead to a long-term commitment to research in Canada.

### 1.3.1 Scope

There are no universally adopted definitions for the terms 'construction automation', 'construction robotics', or 'automated equipment'. To date, so much of current research is concerned with the application of robotic technology, that the field is generally referred to as 'construction robotics'. For the purpose of this thesis, 'construction robot(ics)' refers to construction equipment exhibiting any level of capability allowing it to be programmed to perform a task under automatic control; 'automated equipment' refers to construction equipment which reduces human labour in construction operations using remote, semi-automated, or fully automated control; and 'construction automation' refers to methods or processes which combine automated equipment and/or construction robotics with traditional construction equipment and/or human workers.

Also, while recognizing the great number of possible applications implied by the term 'construction automation', i.e. in tunneling, mining, and highway and road construction, this study limits its view of this term to the field of building construction. The scope is further focused by considering only on-site automation technologies versus those associated with off-site automation, such as prefabrication and pre-assembly.

### 1.3.2 Objectives

This thesis has a main objective and three supporting objectives. The main objective is to examine the feasibility and implementation of automation and robotics in Canadian building construction operations.

Since this is thought to be the first thesis on the subject in Canada, certainly in the province of Québec, the first supporting objective is to provide a comprehensive review of the field of construction automation, covering R&D approaches adopted by different countries, current hardware and software developments, and studies that have been carried out to evaluate feasibility and implementation potential.

The second supporting objective is to identify the capabilities and limitations of current automated and robotic equipment for construction applications.

The third supporting objective is to determine how to implement automation and robotics technologies in building construction operations so that contractors can gain immediate benefits from their use. In particular, this will allow:

1. the development of a methodology for analyzing the implementation of automation in construction operations,
2. the identification of factors which have an important influence on implementation,
3. the evaluation of the extent to which the perceived benefits attributed to automation and robotics in construction, such as increased productivity, quality, and safety, can actually be realized.

### 1.4 Thesis Layout

Chapter II presents a review of work done to date in the field of construction automation and robotics. This includes a survey of current international research focussing on the approaches of different countries, and a review of feasibility and implementation studies. In Chapter III, the knowledge required for a basic understanding of the technological issues facing construction automation is briefly reviewed. Specifically, the capabilities and limitations of current industrial robots are analyzed and compared with those of automated or robotic construction equipment currently under development.

In Chapter IV, the methodology used in the present study to analyze the implementation of automation in construction operations is presented and a case study is identified. In Chapter V, the case study is developed and factors required to achieve the effective use of various levels of automation are analyzed. Chapter VI provides the conclusion of the thesis and recommendations for future work.

# CHAPTER II

# LITERATURE REVIEW

This chapter provides a review of the work done to date in the field of construction automation and robotics. In the first section, the scope of international construction automation and robotics research is reviewed by identifying the approaches of different countries and highlighting their area(s) of concentration. A survey of automated and robotic equipment developed to date is also presented. In the second section, studies which evaluate the feasibility and implementation of automation and robotics in construction are reviewed. Both studies which focus on general or specific applications are covered, and their contributions and limitations are discussed. The observation that current efforts have not focussed sufficient attention on the practical utilization of research findings is drawn, and supports the basic motivation for this thesis.

## 2.1 Current Progress In Construction Automation and Robotics

Construction automation is rapidly developing and quite diversified. Table 2.1 provides a measure of this diversity by presenting a summary of automated and robotic equipment developed to date for on-site applications. Each system is grouped in one of 11 application categories, along with a brief description, the country which developed it, and the stage of development (laboratory prototype, LP, field prototype, FP, or commercially available, C). In developing these systems, researchers in over a dozen countries have adopted different approaches.

| No | Application & Equipment | Description | Country | Stage[a] | Ref[b]. |
|---|---|---|---|---|---|
| A | *Earthwork/Excavation* | | | | |
| 1 | microprocessor controlled equipment | various components and systems, such as production and performance analyzers, vehicle monitoring systems, work rate sensors, wheel slippage monitors, etc. | USA<br>Germany<br>Japan | C<br>C<br>C | 1<br>2<br>3 |
| 2 | laser-guided grading systems | horizontal work plane determined over work area by laser surveying equipment, transmitted to electro-hydraulic feedback system for control of blade level of bulldozers, scrapers, and graders | USA<br>Germany | C<br>C | 4<br>5 |
| 3 | integrated equipment management systems | various systems; typically, main computer monitors locations of trucks and other equipment by means of beacons scattered throughout site. System identifies type and quantity of material being hauled, optimal routes and destinations | USA<br>Japan | C<br>C | 1<br>6 |
| 4 | teleoperated heavy construction equipment | various equipment, such as hydraulic excavators, bachoes, bulldozers, fully operable by means of a remote panel and an equipment-mounted camera observing the worksite | USA<br>Canada<br>Canada | C<br>C<br>C | 7<br>8<br>9 |
| 5 | robotic excavator (REX) | robot excavator for unearthing buried utility pipes; locates pipes by sonar-mapping the site, then plans the digging operation and controls the excavation hardware | USA | LP | 10 |
| 6 | Lancaster University Computerized Intelligent Excavator (LUCIE) | robot bachoe for trenching: high-level rule based control system translates simple instructions into actions by the arm and bucket, taking changing soil conditions into account | UK | FP | 11 |

a: LP=Laboratory Prototype; FP=Field Prototype; C=Commercial
b: References Provided in Appendix A

Table 2.1: Current Applications of Automation and Robotics in Building Construction Operations

| No | Application & Equipment | Description | Country | Stage[a] | Ref.[b] |
|---|---|---|---|---|---|
| B | *Automated Building Systems* | | | | |
| 1 | automated building construction systems | various systems; typically, roof built first, then, as pushed up, other floors constructed beneath. Computer integrated control and optimization of horizontal and vertical material delivery, connections designed for automated assembly, automated welding | Japan<br>Japan<br>Japan | C<br>C<br>C | 12<br>13<br>14 |
| 2 | ATLSS integrated building system (AIBS) | computer integrated structural steel erection system consisting of components with connections designed for automated assembly, automated 6 DOF material handling system, control through design and as-built database | USA | LP | 15 |
| 3 | exterior cladding poitionning system | computer controlled system for vertically sliding into position exterior wall cladding, covering the perimeter of one floor height, for steel framed buildings | Japan | C | 16 |
| C | *Concrete Distribution* | | | | |
| 1 | horizontal concrete distributor (HCD) | 20m-long articulated arm with 4 horizontal and 2 vertical joints, attached to a building column. Automatic nozzle positioning with obstacle avoidance | Japan | C | 17 |
| 2 | partially automated concrete boom for pumping concrete | truck mounted, 5-section boom with computer-aided control of end-effector in job-site coordinates | Germany | C | 18 |
| 3 | computer controlled concrete placing crane | 32m long, four stage articulated crane-mounted concrete placing boom with automatically controlled end-guidance system | Japan | C | 19 |

a: LP=Laboratory Prototype; FP=Field Prototype; C=Commercial
b: References Provided in Appendix A

Table 2.1: Current Applications of Automation and Robotics in Building Construction Operations (cont'd)

| No | Application & Equipment | Description | Country | Stage[a] | Ref.[b] |
|---|---|---|---|---|---|
| D | *Concrete Screeding & Finishing* | | | | |
| 1 | semi-automated concrete screeding machine | retractable laser-guided vibrating screed mounted on 4-wheel drive vehicle | USA | C | 20 |
| 2 | concrete leveling robots | various models; typically, truss-mounted vibrating screed traveling on side-forms (spans vary from 4.5 to 17.5m). | Japan<br>Japan<br>Japan | FP<br>FP<br>FP | 21<br>22<br>23 |
| 3 | concrete levelling and compaction robot (ROL-LIT) | travels on fresh concrete surface, externally vibrates concrete and densifies surface | Sweden | FP | 24 |
| 4 | concrete floor finishing robots | various models; typically, a single or twin trowel assembly rotating around or behind a programmable traveling unit | Japan<br>Japan<br>Japan<br>Japan<br>Sweden | C<br>C<br>C<br>C<br>LP | 25<br>26<br>27<br>28<br>29 |
| E | *Rebar Placement* | | | | |
| 1 | rebar placing robots | various models; typically, crawler mounted manipulator for positionning up to 2.2 tons of rebar. Teach/playback control with manual tying of rebar. Cycle= 1 rebar/1.1 min | Japan<br>Japan | FP<br>C | 30<br>31 |
| 2 | automated rebar bending | various systems; typically, CAD integrated with automated fabrication, stock control, and delivery of rebars | Japan<br>USA | C<br>LP | 32<br>33 |
| F | *Exterior Material-Handling Tasks* | | | | |
| 1 | extended multi joint robot (EMIR) | 6-axis, 22.2m articulated boom with 1400kg payload, automatic path planning, obstacle avoidance, and world model generation | Germany | FP | 34 |

a: LP=Laboratory Prototype; FP=Field Prototype; C=Commercial
b: References Provided in Appendix A

Table 2.1: Current Applications of Automation and Robotics in Building Construction Operations (cont'd)

| No | Application & Equipment | Description | Country | Stage[a] | Ref[b]. |
|---|---|---|---|---|---|
| F | *Exterior Material-Handling Tasks (cont'd)* | | | | |
| 2 | heavy-duty material-handling robot | 6-axis, vehicle-mounted manipulator with 9m reach and 1800kg payload capacity. Manual control system operational, hierarchical control system to be implemented | USA | FP | 35 |
| 3 | large general purpose construction manipulator | telescopic boom + jointed arm on a rotating base with 10m reach and 100kg payload | Australia | LP | 36 |
| 4 | mighty shackle ace | attachment to crane cable allowing remote controlled release of components | Japan | C | 25 |
| 5 | crane & hoist automation systems | various systems; typically, computer controlled tower or wire cranes with limited sensing or metrology systems | UK<br>Israel<br>Netherl.<br>Japan | FP<br>FP<br>FP<br>FP | 37<br>38<br>39<br>40 |
| 6 | Automated Crane Erection System (ACES) | material handling system consisting of a 6 DOF platform mounted on a computer controlled tower crane, for locating, moving, and placing large structural and non-structural elements | USA | LP | 15 |
| 7 | robot crane | kinematically constrained, dynamically stabilitzed robot crane for lifting, moving, and positionning heavy loads over large volumes; supporting fabrication tools; and inspecting structures | USA | LP | 41 |
| 8 | pipe manipulator | 22-ton rough terrain hydraulic crane with a multifunctional 8 DOF manipulator attachement. Heuristic path planning and computer graphic simulation and programming being tested | USA | FP | 42 |

a: LP=Laboratory Prototype; FP=Field Prototype; C=Commercial
b: References Provided in Appendix A

Table 2.1: Current Applications of Automation and Robotics in Building Construction Operations (cont'd)

| No | Application & Equipment | Description | Country | Stage[a] | Ref[b]. |
|---|---|---|---|---|---|
| G | *Interior Material-Handling Tasks* | | | | |
| 1 | material transfer systems | various systems; integration of Automated Guided Vehicles (AGV) + lifts for horizontal and vertical transfer of palletized and containerized components. Tracking and control by guidewire or bar code. | Japan<br>Japan | FP<br>FP | 43<br>44 |
| 2 | material handling for automated building construction | storage and retrieval system combining bar code technology and industrial robots | USA | LP | 45 |
| H | *Interior Tasks: Drywall* | | | | |
| 1 | ceiling gypsum board installation robots | various models; typically, mobile carriage with hydraulic lifting arms which hold, lift, position, and screw gypsum boards onto lightweight steel frames. Navigation by floor-laid guidewire or preprogrammed path | Japan<br>Japan | FP<br>FP | 46<br>47 |
| 2 | drywall panel manipulators | various models; typically consisting of automation of lifting and positionning functions with manual fastening by operator | Japan | C | 25 |
| I | *Interior Tasks: Other* | | | | |
| 1 | Technion Multipurpose Interior Robot (TAMIR) | modified industrial manipulator for erecting lightweight gypsum blocks with interlocking edges; also performs plastering, painting, and tile setting | Israel | LP | 48 |
| 2 | ceiling painting robot (Soffito) | 6 DOF industrial robot mounted on a mobile platform with open loop control of painting and automatic execution of preplanned trajectory | France | FP | 49 |
| 3 | steel fireproofing robots | various models; typically, an industrial manipulator mounted on a mobile base with off-line or teach/playback programming | Japan<br>Japan<br>Japan | FP<br>FP<br>FP | 50<br>25<br>51 |

a: LP=Laboratory Prototype; FP=Field Prototype; C=Commercial
b: References Provided in Appendix A

Table 2.1: Current Applications of Automation and Robotics in Building Construction Operations (cont'd)

| No | Application & Equipment | Description | Country | Stage[a] | Ref[b]. |
|---|---|---|---|---|---|
| I | *Interior Tasks: Other (cont'd)* | | | | |
| 4 | shear stud welding (Studmaster) | Automated welding of shear studs to metal deck. Robot manually positionned at each new weld location | USA | LP | 52 |
| 5 | metal track and stud installing robots (Trackbot & Studbot) | robots for positionning and fastening standard metal tracks on both floors and ceilings and metal studs for interior partition walls | USA | LP | 53 |
| 6 | multipurpose material handling robot | 4 DOF, 495 kg-payload, remote controlled mobile manipulator for positionning heavy components | Japan | C | 30 |
| J | *Masonry Erection* | | | | |
| 1 | Mason's Elevator Handling Machine (MEHM) | operator controlled mobile platform with hydraulic vertical adjustment, incorporating a handling unit with grip for blocks, a mortar pump, and storage for 120kg of blocks | Germany | FP | 54 |
| 2 | concrete block laying robot (Blockbot) | automated mobile platform with hydraulic vertical adjustment, incorporating a 5 DOF manipulator for positionning specially manufactured concrete blocks in a staircase fashion | USA | LP | 55 |
| 3 | experimental masonry construction robot | 5 DOF gantry robot linked to conveyor for dry stacking concrete blocks. CAD utility generates file containing ordered part list, location, and orientation data | U.K. | LP | 56 |
| 4 | Solid Material Assembly System (SMAS) | 6 DOF robot for dry stacking specially designed concrete blocks and joining them with a reinforcing bar | Japan | LP | 57 |

a: LP=Laboratory Prototype; FP=Field Prototype; C=Commercial
b: References Provided in Appendix A

Table 2.1: Current Applications of Automation and Robotics in Building Construction Operations (cont'd)

| No | Application & Equipment | Description | Country | Stage[a] | Ref[b]. |
|---|---|---|---|---|---|
| K | *Inspection* | | | | |
| 1 | wall-climbing robot for inspection | Various models; typically moving over exterior wall surface using crawling mechanism with vacuum suckers, walking mechanism, guidewires, or wheels with propeller for thrust. Applications include intrusive or non-intrusive diagnosis | UK<br>Japan<br>Japan | LP<br>FP<br>FP | 58<br>57<br>26 |

a: LP=Laboratory Prototype; FP=Field Prototype; C=Commercial
b: References Provided in Appendix A

Table 2.1: Current Applications of Automation and Robotics in Building Construction Operations (cont'd)

In Japan, where comparable buildings can be 2 to 3 times more expensive to build than in the US and Canada, construction automation and robotics was made a major research priority in 1982 (Tamura et al. 1989). Since then, a well coordinated R&D effort emphasizing rapid implementation has been established between government agencies, universities, and private industry. Programs such as ART (Advanced Robot Technologies), WASCOR (WASeda university COnstruction Robot), and ACT (Advanced systems for Construction Technologies), have been funded, with a substantial portion, up to 90% in some cases, of budgets allocated to hardware (Albus 1986; Cho 1988; Okada 1988; Tamura 1989). Consequently, the top Japanese design-build organizations have been vigorously pursuing construction automation research, spending approximately 1% of total contract volume and employing about 1000 people on in-house R&D alone (Albus 1986).

The Japanese approach to construction automation was motivated by either the need to robotize a task due to inherent hazards to the human operator associated with its performance, or by potential labour savings due to task simplicity, high volume, and repetitiveness. The result is that a significant number of automated equipment and robots have been developed which directly replace (or reduce) human involvement in specific tasks. Although this approach yielded numerous early practical applications, many proved very difficult and costly to implement.

Construction automation research in Japan has developed in three directions, all hardware-oriented: first, fundamental research into enabling technologies such as sensing and control, mobility and navigation, and positioning technologies for the site; second, single purpose automated equipment for field applications, such as fireproofing (I3)[1], concrete floor finishing (D4), and ceiling panel installing (H1); and third, large-scale automated construction systems, such as Roof Push-Up Construction (B1) and automated exterior cladding installation systems (B3).

In Europe, many research activities related to construction automation are part of pan-European collaborative efforts. For example, within the European community, the EUREKA, ESPRIT, and BRITE programs support a number of construction automation related R&D projects. These include: at least three concerning the automation of masonry construction; the ATLAS project whose goal it is to develop the architecture, methodology and tools for computer integrated large scale engineering; the PANORAMA project which aims at developing an autonomous transport system for partially structured environments such as construction sites; the MACHINE project, focussing on the development of semi-autonomous cranes and hoists; and the LAMA project whose purpose it is to develop large scale manipulators. Benefiting from the spin-offs of these large research projects, many private equipment and robot manufacturers are supporting the short-term efforts required to commercialize the newly developed technologies.

In Great Britain, a feasibility study undertaken in 1987 by the Construction Industry Research and Information Association (CIRIA) concluded that survey/inspection of buildings and civil engineering structures was the most promising application area for advanced robotics (Radevski and Garas 1988). In 1992, a national group consisting of contractors, consulting firms, equipment manufacturers, and academic institutions

1 For the remainder of this thesis, alphanumeric characters provided in parenthesis refer to the automated and robotic equipment listed in Table 2.1.

launched a three year programme to develop the enabling technologies required to implement a working prototype for building inspection applications (K1). Other important construction automation research includes building design for automation at the Bristol Polytechnic and the University of Reading, artificial intelligence techniques for planning and control of construction tasks at the University of Nottingham, and automation of excavation at the University of Lancaster's construction robotics research center (A6) (Garas 1992).

In West Germany, after an initial investigation of possible applications in 1986, the Ministry for Research and Technology sponsored a number of construction-related projects based on the approach of adding existing or state of the art components to conventional machinery (Wanner 1988). The principal project focussed on the development of large programmable manipulators for a variety of applications such concrete placing (C2), material handling (F1), and fire-fighting. Another area which is quite advanced involves the development of microelectronic components and systems for mobile construction machines (Wanner 1992). Also, the Germans' preference for bricked residential buildings has led to many efforts in automated masonry construction. These applications, which include masonry cranes, semi-automatic brick laying machines, and prefabrication of complete walls in production plants, have, however, not been entirely successful on a large scale (Pritschow et al. 1993).

In France, from 1984 to 1989, the Ministry of Construction supported many efforts to promote construction robotics, including: feasibility studies for building and road construction applications; short-term projects such as the development of robotic tower cranes and site positioning systems; and experimental research on prototypes such as

SOFFITO (I2), Europe's first mobile robot designed especially for the construction industry. In 1990, an analysis of the results of these early efforts, along with skepticism about the potential for on-site robotics by industry practitioners, led to a reassessment of research directions (Salagnac 1992). Since then, the priority has been to focus on the development of software interfaces between design databases and component manufacturing systems, planning and scheduling systems, and material handling and installation robots.

In Sweden, feasibility studies have been undertaken by the Swedish Council for Building Research and the Swedish Construction Federation emphasizing the rationalization of prefabrication for robotic assembly and specific individual processes in need of improvement (Rahm 1988). Masonry was placed at the top of the list followed by roofing, cleaning, plastering and painting, and concreting (D3, D4) (Ahman 1992). In Finland, a major three-part programme (Information and Automation Systems in Construction) has been initiated in 1986 by the Technical Research Center (Koskela 1988). The first part, focusing on construction robotics, established a joint three year Norwegian-Finnish feasibility project, begun in 1988 with the cooperation of 18 private companies. Nine areas have been chosen for analysis, with pilot projects already underway in crane automation and masonry construction. The core task of the remaining two parts is to develop and test a national software structure for a construction project database.

Israel has been at the forefront of construction automation since 1984 when the Israel Institute of Technology, in cooperation with Carnegie Mellon University (CMU), sponsored the first methodological feasibility study of robots in construction (Warszawski 1984). Since then, interest in the automation of interior finishing tasks has led to the development of a multipurpose interior finishing robot (I1). Other research topics include automation of hoisting (F5) and the study of robot-environment interaction and project-wide databases (Warszawski 1992).

In reviewing the American approach to construction automation and robotics, it is apparent that an early emphasis was placed on the involvement of the practicing architecture, engineering, and construction communities. Agendas for construction automation research, defined at industry-university workshops in 1985 (Evans 1986; Ibbs 1986) and 1991 (Tucker 1991) have consistently focussed on the following priorities: (1) integrated project-wide databases with 3D CAD; (2) graphic simulation of construction methods, planning, and scheduling; (3) measurement technology for creating as-built databases and determining the real time position of robots on site; and (4), interface standards between CAD databases and shop floor/field robots.

Thus in the US, a higher priority is placed on software R&D than on hardware. The reason is two-fold: first, software is often a prerequisite for hardware, and second, research on computer applications such as expert systems, graphic simulation, and integrated databases is much less expensive than research on automated equipment and robotics for field applications. With respect to automated equipment and robots for on-site applications, industry practitioners have proved to be very skeptical, and consequently, only a few universities pursue it regularly (Tucker 1991).

Since a complete report of the research undertaken by American universities can be found in the literature (Skibniewski 1992; Tucker 1991), a summary of the principal efforts by the most active institutions is presented. At Carnegie Mellon University (CMU), whose pioneering efforts sparked interest in this field, research is directed towards the development of a complete autonomous machine that can accomplish a mission in a dynamic environment. The principal field of application is excavation, and a prototype robot excavator (REX) has been built to study issues such as domain modeling, subsurface measurement technology, sensor fusion, and strategic task planning (A5). The Center for Advanced Technology for Large Scale Structural Systems (ATLSS), established at Lehigh University, coordinates research in automated construction and connection systems (B2, F6). At the National Institute of Standards and Technology (NIST), the Center for Building Technology is conducting the Robot Crane Technology Project (F7), as well as other research on CAD database exchange standards (Killen 1989).

Stanford University is investigating control and software structures for computer integrated construction and data-acquisistion methods for real-time control of field robots. At the Massachusetts Institute of Technology, task-specific robots (I4, I5, J2) are being pursued as part of the Integrated Construction Automation Design Methodology. Design, control, and simulation of large scale manipulators for construction is the focus of research at the University of Texas at Austin, with one application, piping, receiving considerable attention (F8). The Construction Automation and Robotics Lab at North Carolina State University is pursuing AI/CAD systems for integration of design, fabrication, and delivery of steel reinforcing bars (E2). Purdue University is developing a decision support system for construction robot implementation and management (Skibniewski et al. 1992).

## 2.2 Feasibility and Implementation Studies

While considerable efforts have been directed towards hardware and software R&D, other efforts have focused on evaluating the feasibility of automation and robotics in construction. A review of construction automation feasibility studies shows that the primary question asked has been: to which construction activities can *robotics* best be applied? The motivation for this approach derives from the fact that since R&D resources are limited, applications of automation should be carefully selected before commencing research on any specific project.

In answering this question, researchers have, typically, attempted to identify automation opportunities in a wide range of applications by evaluating various factors for each, combining them in a single measure of "feasibility", and ranking them within their particular classification system. The methodologies vary from one another in the level at which the application is being analyzed (construction division, activity, operation, task), the factors considered (technological, need, economic), the method of evaluating factors (personal experience, statistical) and the method of combining and ranking results (weighed sum, analytic methods, expert system). In the following review, the methodologies of various studies are highlighted and results will be reported where available.

Warszawski (1984) was the first methodological study of robots in building construction and represents a major contribution in that it led to the increased awareness of the subject. Based on a general evaluation of ten basic building activities (positioning, connecting, attaching, finishing, coating, concreting, building, inlaying, covering, jointing) with respect to seven technical requirements (reach, payload, end effector, feeding method, control, sensing, and mobility), Warszawski concluded that almost all building construction operations (except for site work and mechanical systems) can be performed by four generic multipurpose robots, shown in Figure 2.1. Activities that require covering or conditioning of large continuous surfaces are cited as the most amenable to robotization, followed by activities that require "moving the end effector at different locations in a predetermined pattern", such as welding, bolting and jointing. Found least amenable are those activities requiring handling and assembly of components, which can involve "picking, orientation, precise positioning, and often temporary supporting of objects".

Halpin et al. (1987) performed a feasibility analysis largely based on the subjective evaluation of experienced construction industry practitioners. Through a series of brainstorming sessions, experienced practitioners in construction design, management, and research, evaluated 33 construction processes with respect to 5 technological and 10 need-based factors. Each process was rated on a scale of 1 to 10 (the higher the rating the higher the need or the more feasible the technology), and the ratings were combined and normalized using participant-defined weighting ratios. The results, shown in Table 2.2, indicate that surface processing tasks are most amenable to robotic implementation, while tasks which require the positioning and attaching of discrete objects are not feasible using present robotics technology. The analysis was later expanded to include an expert system based fuzzy set model for linguistic analysis, evaluation, and translation, in order to rationalize the subjective responses of the participants (Kangari and Halpin 1990).

In his Master's thesis, Alonzo-Holtorf (1987) analyzed the automation potential in commercial building construction in a somewhat more objective way. An automation susceptibility index was developed for nine building subsystems, namely, foundation,

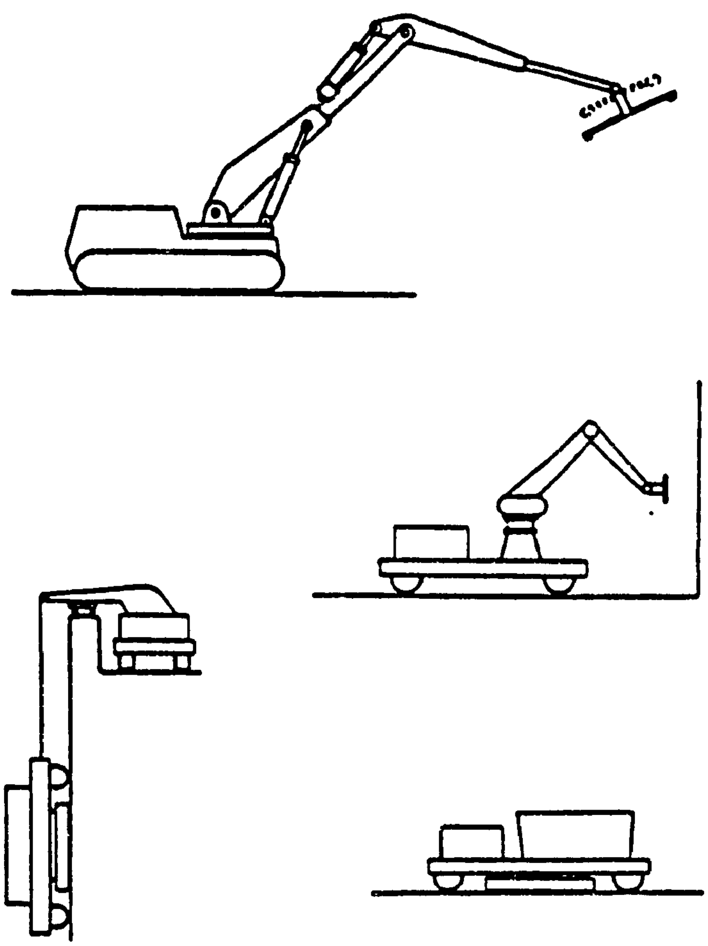

Figure 2.1: Four Basic Building Robot Configurations According to Warszawski Study (Warszawski 1984).

| Construction Process | Needs Rating (10=greatest) | Technology Rating (10=most feasible) | Construction Process |
|---|---|---|---|
| tunneling (cut/muck) | 9.7 | 9.8 | tunneling (cut/muck) |
| tunneling (hand) | 9.5 | 9.8 | tunneling (hand) |
| painting | 9.2 | 9.8 | tunneling (precast) |
| sandblasting | 9.2 | 9.5 | painting |
| bush hammering | 8.7 | 9.2 | steel fabrication |
| tunneling (cast in place) | 8.7 | 9.1 | wall finishing |
| wall finishing | 8.4 | 9.1 | ditching |
| drywall | 8.3 | 9.1 | grading |
| tunneling (precast) | 7.6 | 9.1 | layout/survey |
| concrete placement | 7.4 | 8.8 | sandblasting |
| tiling | 7.4 | 8.6 | fireproof spray |
| pile driving | 7.2 | 8.0 | post tensioning |
| fireproof spray | 7.0 | 7.4 | rebar placement |
| masonry | 6.8 | 7.1 | concrete placement |
| steel fabrication | 6.4 | 6.9 | masonry |
| rebar placement | 6.0 | 6.8 | tunneling (cast in place) |
| precast cladding | 5.6 | 6.8 | crane operations |
| piping underground | 5.1 | 6.5 | bush hammering |
| precast structural | 5.0 | 6.5 | slurry walls |
| formwork | 4.9 | 6.3 | tiling |
| insulating (siding) | 4.8 | 6.3 | precast cladding |
| ditching | 4.7 | 6.2 | insulating (siding) |
| steel (structural) | 4.7 | 5.8 | drywall |
| grading | 4.3 | 5.2 | piping underground |
| scaffolding | 4.1 | 4.9 | steel (structural) |
| slurry walls | 4.1 | 3.7 | pile driving |
| layout/survey | 3.2 | 3.5 | precast structural |
| decking | 3.1 | 3.5 | sprinkler piping |
| post tensioning | 3.1 | 2.5 | decking |
| sprinkler piping | 3.0 | 2.5 | duct work |
| crane operations | 2.7 | 0.3 | formwork |
| duct work | 1.7 | 0.2 | scaffolding |
| piping plumbing | 1.0 | 0.2 | piping plumbing |

Table 2.2: Ranking of Robotic Feasibility for Various Construction Processes According to Halpin Study (Halpin et al. 1987)

substructure, superstructure, exterior closure, roofing, interior construction, conveying, mechanical, and electrical. The index for each given subsystem is a weighted sum of six economic and one "technical susceptibility" factor. Individual values for the economic factors are estimated based on aggregate data from the US Bureau of Census and Means Costs Estimating Handbook, while those for technical susceptibility and the assignment of individual weights, are based on the researcher's own experience. The results indicate that, of the subsystems considered, the most amenable to automation are exterior closure, interior construction, and superstructure.

In an effort tailored more accurately to reflect the requirements of a specific contractor, Bashford (1992) applied the Delphi method, a technique used for structuring the communication process among a group of individuals confronted with a complex problem, in order to determine which of a major UK contractor's activities would benefit most from robotic development. The factors considered were frequency of an activity causing disruption and potential benefits and problems of robotization. Concrete floor finishing, grading, site stock control, drainage, and reinforcement cage fabrication, were found to be the preferred activities for robotization.

The aforementioned studies have identified a number of fields where the *general application of robots* would be beneficial. The term 'general application of robots' reflects the two restrictions which characterize the studies. First, only the potential application of *robots* are addressed, and not the more general issue of automation. Second, because the application categories considered are so broad, ranging from entire divisions such as superstructure, to generic construction operations such as concreting or painting, the researchers' or participants' evaluation of the factors considered could only be based on preconceived notions or unknown assumptions regarding the configuration of the robotized operation.

A number of researchers have recognized that the feasibility of automation should be defined at an appropriate level to be meaningful. In the early stages of this research, the author proposed a method to evaluate feasibility based on the premise that detailed technical and economic factors should only be considered once areas with the greatest need for improvement were identified (Fazio et al. 1989). An Automation Index was therefore devloped to evaluate the need for improvement in various trades. Each trade is considered in terms of strategic (safety, labour shortage, quality), tactical (seasonality, overtime, volume of work), and operating (labour utilization, work context and content) needs. Since the structure of the Automation Index permits the use of analytical prioritizing methods, weights can be assigned based on local or regional needs. Trades which 'score' highly on the Automation Index can then be broken down into operations and tasks for technical and economic analysis with respect to automation.

In her PhD thesis, Demsetz (1989) also proposes a two step approach. First, a preliminary task selection is carried out based solely on the potential for benefit (automation and robotics are not mentioned in order to prevent participant's preconceived notions from biasing the results). Next, a design team assesses the various ways in which each task can be accomplished by dividing the work between man and machine to optimize the contribution of each. Everett (1990) has developed a list of 18 basic tasks which are common to numerous activities, and proposes to prioritize them based on economic and technological factors, competing technologies, and labour acceptance, and to compare them across activities. Guo and Tucker (1993) have proposed a method to quantify the need for automation, defined by safety, productivity, worker utilization, superhuman handling, and quality, using 42 generic tasks common to various operations. An Automation Concern Index is generated using the Analytic Hierarchy Procedure to assess weights. The ACI must then be compared with technical and cost considerations to identify the best potential candidates for automation.

This review shows that considerable attention has been focused on prioritizing construction automation and robotics research efforts. While this approach has led to a basic understanding of the factors justifying the automation of various types of construction activities or tasks, efforts towards a more practical utilization of the research findings have been very limited. Skibniewski et al. (1992), have done considerable research on a neural network-based Construction Robotic Equipment Management decision support system (CREMS). Intended for large Architecture/Engineering (A/E) firms with a fleet of construction robots, the system incorporates modules for construction task analysis, *robot* capability analysis, *robot* economic evaluation module, and *robot* implementation logistics. Others have analyzed the general economic benefits of using construction *robots* (Warszawski 1984) or the specific benefits and costs of implementing a *robot* in a particular application (Najafi and Fu 1992; Rosenfeld et al. 115; Skibniewski 1985).

However, by limiting their analysis to the evaluation of *robots*, these studies have addressed the topic in a superficial way. For, when contractors plan a construction operation, they must determine the optimal combination of resources which will allow them to execute the job within constraints of time, cost, and quality. Thus, the analysis of construction applications must consider that different levels of automation, i.e., manual, mechanized, semi-automated, and fully automated, may have to be combined within a particular operation, without requiring dependent operations to be of equal level of automation, but allowing the benefits of each to be fully realized. There is therefore a need to address contractors' planning and implementation concerns in a broader way.

# CHAPTER III

# TECHNOLOGY ASSESSMENT

This chapter provides a brief review of the knowledge required for a general understanding of the technological issues facing construction automation and robotics. The capabilities and limitations of current industrial robots are first presented. This serves as the basis for comparisons with the general requirements for robotics in construction applications, and leads to the broader issue of automation. Issues deemed crucial to construction applications are highlighted and, when applicable, related to the specific examples of automated or robotic equipment developed to date.

## 3.1 Industrial Automation and Robotics Technology

In North America, an industrial robot is defined by the Robotic Industries Association as a "reprogrammable, multifunctional manipulator designed to move parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks" ("Industrial Robot" 1986). These tasks are usually grouped into seven application categories which include material handling, machine loading, spraying, welding, machining, assembly, and inspection (Meystel 1988). In the Province of Quebec, as of January 1989, there were approximately 300 industrial robots, mostly for painting and welding applications in the automotive industry (Dupaul 1989).

An industrial robot generally consists of three subsystems, namely, the mechanical components, the programming and control system, and the sensors. These subsystems are designed and assembled to produce a robot that will meet specified performance standards, usually defined in terms of positioning, work volume, speed, and load capacity. A taxonomy of a generic industrial robot and its performance characteristics is shown in Figure 3.1. In this section, mechanical components and performance characteristics are first discussed, followed by programming and control systems, and sensing. Mobility, which represents in many ways a synthesis of mechanics, programming and control, and sensing, and which is not typically required by industrial robots, is also discussed in this section to account for the broader range of conditions for which construction robots must be designed.

### 3.1.1 Mechanical Components and System Performance

Mechanical components are the parts that move or that produce motion, and include the *manipulator* which serves as structural system, the *actuators* that power the joints, and the *end effector* by which objects are grasped or acted upon. Most robot *manipulators* are composed of rigid links connected by joints having a single degree of freedom (DOF), either translational or rotational. The joints are partitioned such that the first few (usually 3) closest to the base are used to position the manipulator, and the last few (3 or less) are used to orient the end effector. Four basic manipulator configurations are shown in Figure 3.2, and include the following types: (a) Cartesian, with translational joints only; (b) Cylindrical, with one rotational and two translational joints; (c) Spherical, with two perpendicular rotational joints and one translational; and (d) Revolute, with three rotational joints, two of them coplanar.

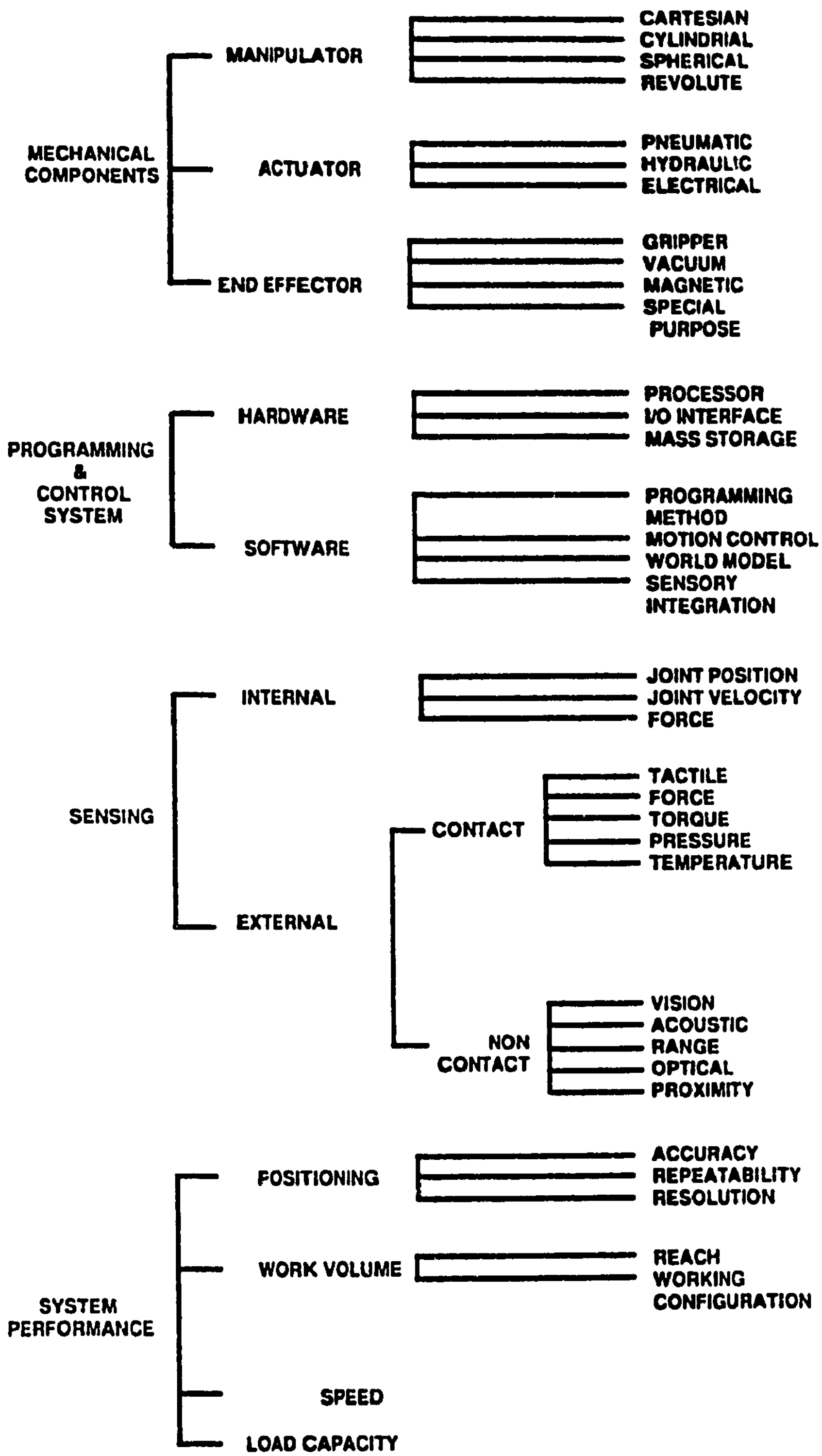


**Figure 3.1: Taxonomy of a Generic Industrial Robot and its Performance Characteristics (Ayres et al. 1985)**

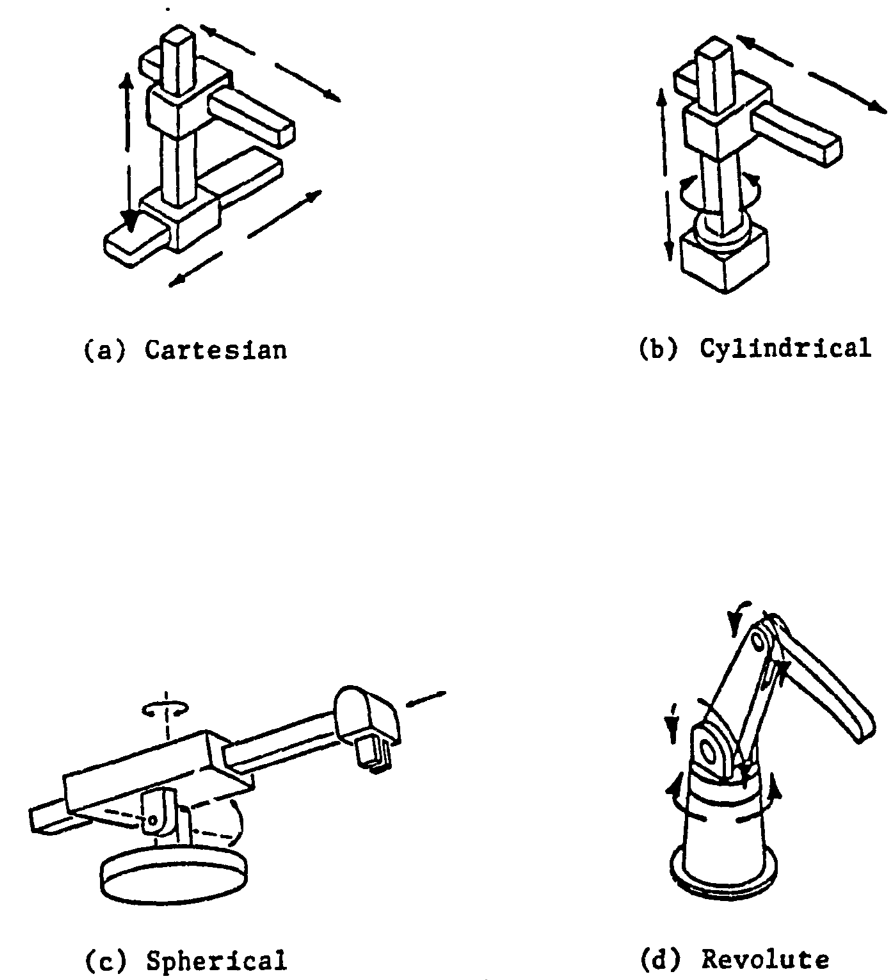


Figure 3.2: Basic Industrial Manipulator Configurations (Ayres et al. 1985)

*Actuators* are the motors that deliver power to the joints and end effector. Presently, industrial robots are either hydraulically, pneumatically, or electromagnetically driven, with the latter type being most popular (Fisher et al. 1992). Power is transmitted from the actuator in the robot's base to the joints via transmission systems and gear trains. In a typical robot however, only 50-90% of the power is delivered from the motor shaft to the joint, the rest is lost through friction (Day 1987). Actuator power is one of the major limitations of load capacity, as current manipulators can typically lift approximately one tenth of their own weight[2] (Ayres et al. 1985).

The *end effector* is installed at the end of the robot's wrist and is usually custom designed to match process requirements. An end effector can be a gripper or a dedicated tool, such as a spray gun, vacuum cup, or electromagnet. For present industrial applications, the 1 DOF two-fingered gripper is the most popular, although three-, and five-fingered types have been developed but still lack efficient control algorithms (Albus 1984; Tanie 1985). Studies also indicate that 80% of industrial assembly tasks could be accomplished using only two- or three-fingered grippers with tactile sensors, and that three fingers may be sufficient to reproduce the predominant grasp of the human hand[3] (Grupen et al. 1989).

The last unit in Figure 3.1 lists the parameters which describe how the robot system performs as a whole. *Positioning* describes how well the robot is able to bring the end effector to a desired location, and is characterized by three parameters: *Resolution*, indicates the smallest incremental motion that can be produced by the manipulator;

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2 By comparison, the human arm can lift approximately ten times its own weight (Albus 1984).

3 The human hand has 20 DOFs: Each finger except the thumb has three joints allowing 4 DOFs, the thumb has two joints for 3 DOF, and the palm has 1 DOF (Tanie 1985).

*Repeatability*, the most commonly specified positioning parameter, indicates how closely the end effector can return to a position it was at previously; And *accuracy*, indicates the ability of a robot to position its end effector at a point, X Y Z, in space. *Work volume* is the region around the robot which can be reached by the end-effector, and depends on manipulator configuration and reach. *Load capacity* and *speed* are self-explanatory, and are closely related through strength and stability conditions of the robot structural system.

### 3.1.2 Programming and Control

Although a robot's versatility is largely derived from it's physical structure and components, it's operational flexibility is governed by the types of motions or operations that can be programmed into, and executed by, the control system. Robot programming is the process of generating the instructions required to preform a task, and can vary in complexity from explicitly specifying a sequence of target points to providing high level goals. The control system in turn signals the actuators in accordance with the instructions, and ensures that the end effector is moved to the specified point or along the specified path, according to a specified velocity or acceleration.

In general, robot programming systems can be classified in five categories, as shown in Figure 3.3. The Figure indicates the level at which the robot is controlled and provides sample instructions showing the detail in which robot operations are expressed.

At the lowest level, no formal language exists, as commands are dependent on the physical structure of the robot. Robots under such control are referred to as limited

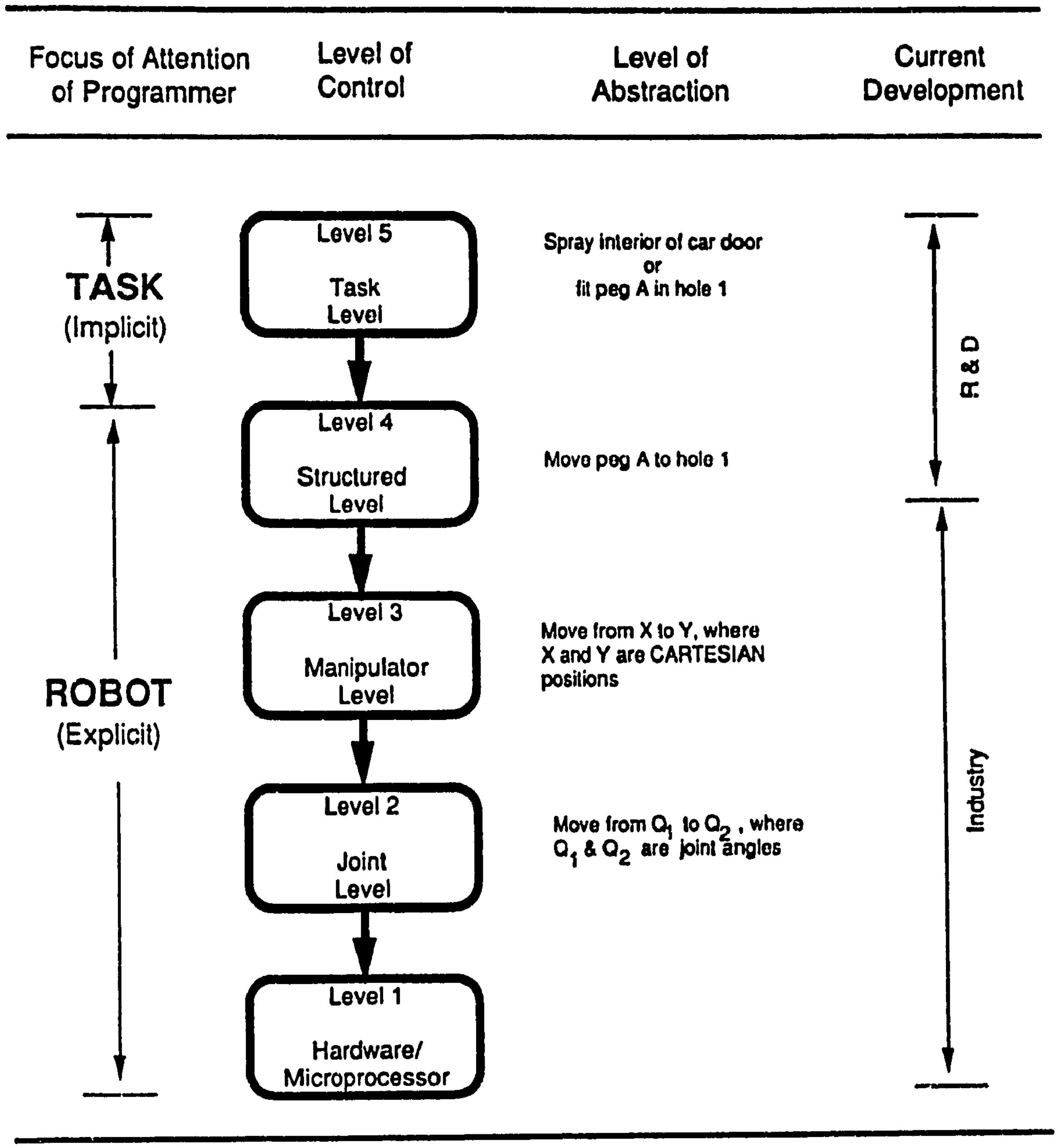


Figure 3.3: Programming and Control Levels.

sequence or 'bang-bang' robots, because their motions are terminated by physically banging into fixed stops at the end of each stroke. At first, these stops were adjustable mechanically and could not be changed during operation. This limitation was overcome by placing multiple stops along the motion path, whose insertion could be controlled by pneumatic cylinders, stepping switches, or programmable controllers. Although fast, accurate, and relatively inexpensive, limited sequence robots are too inflexible for anything other than routine pick and place applications (Critchlow 1985; Groover 1986).

At the second level, a task is specified in terms of the joint control commands required to drive the individual actuators. This method is known as 'teaching by showing' or guiding, and is illustrated in Figure 3.4. The robot's joints are moved manually or with the assistance of a control box (called a teach pendant), until the combination of all axial positions yields the desired position of the end effector. The corresponding configuration is stored by recording the joint angles, and the procedure is repeated for the next target point. The resulting program is a sequence of vectors of joint coordinates plus activation signals for the end effector (Lozano-Perez and Brooks 1985).

Currently, most industrial robots are programmed in this manner (Critchlow 1985; Gini and Gini 1991). The main advantage of teaching stems from the fact that it is easier to show someone what to do than it is to describe it. Consequently it is easy to learn and can be accomplished by shop workers who are familiar with their tasks. Teach by showing is, however, limited in two main respects: first, the need for the robot during programming precludes its use in production, and therefore if the batch size is too small, it may take longer to prepare the program than to run it; and second, teaching complex motions, such

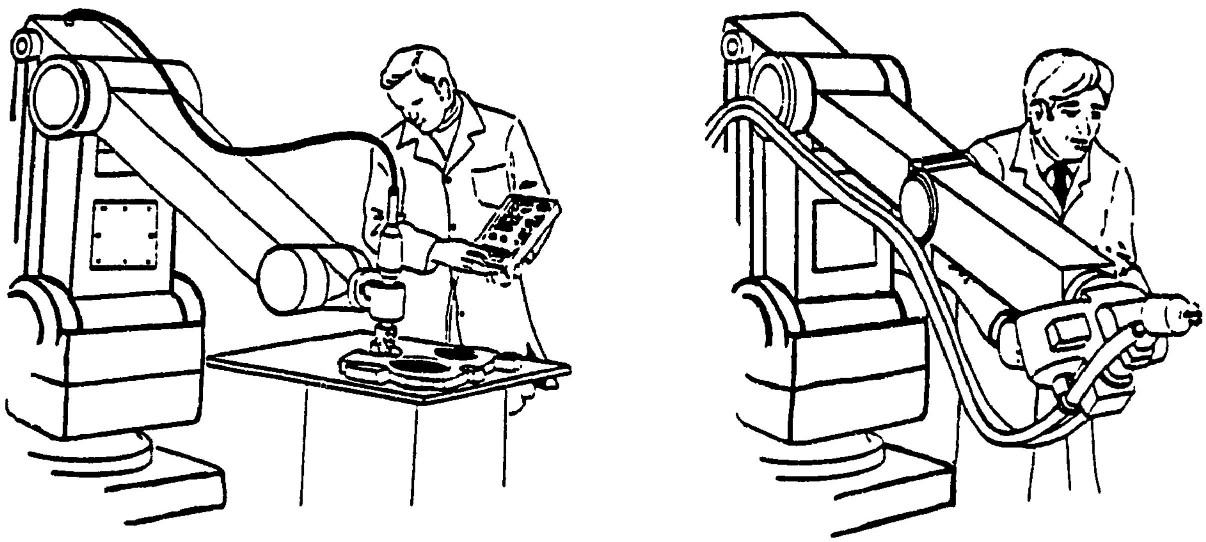

Figure 3.4: "Teach by Showing" Programming Method

as those for spraypainting or spot welding, may require entering hundreds of points; a long and tedious task with a high probability of error (Bonner and Shin 1982; Critchlow 1985; Groover 1986).

At level 3 (manipulator level), the use of a robot programming language (RPL) becomes available. Tasks are described by explicitly specifying both the sequence of actions which are required to carry them out and the positions through which the robot must pass. The robot's only knowledge of the working environment is represented by the values encrypted in program variables: for instance, the size of an object to be grasped is represented by the value of the opening required for the gripper, not as a feature of the object.

Although the capabilities of manipulator-level languages vary widely, they represent the current level of most commercial programming systems (Bonner and Shin 1982; Gini and Gini 1991; Lozano-Perez and Brooks 1985). The main advantage of manipulator-level RPLs, relative to teaching, is that they permit branches or subroutines to be addressed by sensors and accept sensory values from external sources. However, since all motions are pre-computed based on fixed object positions, the use of sensor data to continuously control the movements of the robot in run time is not possible.

Knowledge of the environment, the key to a truly intelligent robot programming system, becomes available in limited form at level 4 (structured level) (Lozano-Perez and Brooks 1985). Here, RPLs typically support the representation of object positions by coordinate frames[4] and the manipulation of object frames via tranforms. Motion is therefore generally defined in terms of transformations of the frame of the robot hand rather than explicit manipulator positions. The main advantage of structured level RPLs is also their major drawback: while coordinate transformations lead to a more general way of expressing motion, they are much more difficult to understand and use. RPLs that incorporate some level of a world model are expected to have an industrial impact within a decade (Gini and Gini 1991).

The development of RPLs is generally recognized one of the most significant aspects of the evolution of industrial robots (Critchlow 1985; Lozano-Perez and Brooks 1985). Presently there are almost as many languages as there are robots, each manufacturer having developed its own robot specific system (VAL from Unimation, AML from IBM, KAREL from GMF). However, many industry practitioners feel that current RPLs are developed from the programmer's aspect rather than from the user's point of view, and consequently are too difficult to use (Gini and Gini 1991; Voltz 1988). It is not unusual to spend between three to six man-months to develop and test new, reasonably complex programs (Gini and Gini 1991). Even when the tasks are relatively simple, as are today's industrial robot tasks, the cost of programming a single robot application may be comparable to the cost of the robot itself (Lozano-Perez and Brooks 1985).

At the highest level of programming sophistication, level 5, coordinate transformations and other lower-level computations are concealed, sinplifying the robot-user interface, thus allowing the task to be described in terms of objects to be manipulated instead of

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4 Frames are the most common representation for object locations in robotics; they represent a coordinate system in cartesian space and are expressed by a 4X4 matrix consisting of a 3X3 submatrix specifying orientation and a vector specifying position.

motions to be performed. The task of inserting a peg in a hole would simply be described as 'Insert peg in Hole', instead of as the sequence of robot motions required to accomplish the insertion. At the highest level of abstraction, a task-level description would only require a specification of the final goal to be achieved, such as for example, 'Paint Interior of Car Door'. The most advanced task-level systems developed to date, operate at a much lower level of abstraction and have been only partially implemented (Lozano-Perez and Brooks 1985). It is unclear how long it will take for task-level languages to leave research laboratories for the real world (Gini and Gini 1991).

### 3.1.3 Sensing

The vast majority of current industrial robot applications are performed without significant external sensing (Critchlow 1985; Kak 1985; Lozano-Perez and Brooks 1985). In such cases the environment is engineered so as to eliminate all significant sources of uncertainty and the task can be specified as a sequence of desired robot configurations. However, in less constrained situations, where exact knowledge of the world cannot be fully known, future applications will depend very strongly on the use of sensors to translate the physical properties of the world into information required for carrying out a task.

Sensors are used for monitoring both the internal state of the robot and the external state of the world. Internal sensors measure the variables that are necessary for low-level control of the manipulator, such as joint position, velocity, and force, and have a great influence on the resolution and accuracy of the manipulator (Kak 1985). External sensors are usually divided into two categories: non-contact, such as vision, proximity, and acoustic systems, and contact, such as tactile, force, and torque. The principal uses of external sensors are: to initiate and terminate motions (the most common use in existing systems), to choose among alternative actions, to obtain the identity and position of objects or features of objects, and to allow the robot to comply with external constraints (Lozano-Perez and Brooks 1985). The most commonly used external sensors in current industrial applications are vision and tactile systems (Kak 1985; Nicholls and Lee 1989).

Vision is recognized as the most powerful of sensory capabilities for allowing robots to work in unstructured environments, and is by far the most developed of the sensor technologies. It conveys an enormous amount of information, representing, in humans, approximately 90% of total sensory input (Ayres et al. 1985). The field of machine vision has yielded developments which are presently successfully applied mostly in monitoring and inspection tasks where the environment is well known and highly constrained through the use of, for example, controlled lighting to allow specialized processing of shadows, controlled texture and shading for extraction of surface geometry, and restricted views, such as overhead views of isolated objects (Domey and Burtnyk 1987). As the degree of structure in the environment is reduced, many methods become unreliable, and, for the general unconstrained case where viewing direction is arbitrary, lighting is conventional, and objects are unknown or partially occluded, considerable research is still required (Rosenfeld 1986).

The difficulty of vision systems in dealing with unconstrained environments and the growing application of robots in assembly operations has led to an increased interest in tactile since the early 1980's (Nicholls and Lee 1989). At the lowest level, tactile sensors can only determine the presence or absence of an object at a particular point or array of points. A more advanced type uses an array of pressure sensitive cells to generate gray values that are proportional to the force applied to the sensor. The most capable of these sensors can also sense surface orientation, returning a surface normal vector (Allen 1987). Tactile sensing is also of particular importance in obtaining force feedback in situations where the motion of the manipulator is partially constrained due to contact with one or more surfaces. A variety of devices have been developed which sense the forces and torques applied at the end effector either indirectly, by measuring the forces acting on the joints of the manipulator, or directly, by measuring the forces at the wrist or the fingertips. A recent survey suggest however that industrial use of tactile sensing technology is still small, and that it is still in its infancy with respect to vision (Nicholls and Lee 1989).

While human beings, who rely on five senses to obtain information from the world (vision, hearing, touch, taste, and smell), do not distinguish between detecting signals and interpreting them, robots "must be explicitly instructed on how to represent and store the physical signals, process them, extract required information, and communicate the information to the robot or other machines" (Ayres et al. 1985). This places two key requirements on programming systems: first input and output mechanisms must be provided for acquiring sensory data, and second efficient representational and computational capabilities are required for interpreting the data. The latter requirements are considered to be the major constraining factors on the achievable level of robot intelligence and represent, according to many researchers, the most important research problems in robotics (Gini and Gini 1991; Paul 1983; Voltz 1988).

### 3.1.4 Mobility

The provision of general mobility for a robot is considered by many to be one of the greatest challenges in robotics, as it represents one of the most complex problems in mechanical, programming, and control systems integration (Albus 1984; Meystel 1988). Autonomous travel imposes several stringent requirements on the design of a vehicle and its subsystems: the robot's sensors must perceive the vehicle's instantaneous position, orientation, local obstacles, and enough of the distant surroundings to plan a route towards the final goal; the computer system, while fitting on the vehicle and not exceeding its payload, must have sufficient capacity to interpret and integrate multi-sensor data, plan vehicle motions, and control actuator responses with enough speed to effect the desired motion; the vehicle itself must have a self-contained power supply to support all the processing, sensing, and locomotion activities, and must provide the structure to protect all these delicate components from shock, vibration, temperature, dust, and other harsh elements.

Quite obviously, the less structured the environment, the greater the complexity of the mechanical systems and the reliance on sensing. With respect to mechanical systems, the following factors must be considered: configuration (wheeled, tracked, legged), steering (articulated like a car, skid, omnidirectional), suspension (rigid, adaptive), braking (passive, active).

In the simplest of situations, a highly structured factory environment with a smooth floor, a vehicle with a rigid suspension and articulated steering providing direct displacement control of one surface DOF is sufficient[5]. Control of such vehicles is straightforward and easy to implement (Harmon 1987). If the environment is cluttered with obstructions, then the ability to move in any direction may be more important, and omnidirectional steering, providing direct displacement control of all three surface DOFs, is required. Direct control of the three surface DOFs is also necessary for accurate surface placement of any vehicle. If the surface is not quite flat, then an adaptive suspension becomes necessary (for controlling the three terrain related DOFs), and if the vehicle's mass exceeds a small amount, it needs active braking. As the environment becomes less smooth, caterpillar tracks become more useful, and are also capable of climbing stairs and breaching obstacles. For rough and unstructured terrain, legs are the best choice, but experience shows that they are difficult to control due to their complexity (Waldron and McGhee 1986).

As soon as the robot goes mobile it looses its physical reference in the world and is therefore totally reliant on sensors to estimate its position. Two essential forms of guidance are distinguished, namely, fixed-path and free-ranging. Fixed path guidance systems typically require networks of rails, or inductive floor-buried wires or surface painted lines. Robots guided by inductive fixed-paths, known as automatic guided vehicles (AGVs), are well understood and have been successfully applied in industrial material handling applications since the late seventies, producing significant productivity improvements (Miller 1985). This type of guidance is adapted to the specific layout of

5 Of the six space DOFs, three are determined by the contours of the surface (i.e., vertical position, and pitch and roll rotations). The remaining three DOFs determine surface position and orientation, and include longitude, latitude, and heading (rotation about the surface normal). Articulated steering provides displacement control of the longitudinal DOF, skid steering allows positional control of both longitude and heading, and omnidirectional allows positional control of all three surface DOFs.

the factory floor and requires simple sensory and control strategies to steer the vehicle. The major drawback of fixed-path guidance systems is their inherent inflexibility due to the high cost of laying down the paths and the difficulty of altering them once set.

Free-range guidance systems include relative position sensors, such as dead reckoning[6] and inertial guidance systems which provide continuous knowledge of position, and absolute position sensors, such as position reference beacons and ultrasonic or optical imaging systems which provide the robot's absolute position in the environment. Presently, reliable free-range guidance is only available from systems which combine information from both absolute and relative position sources, thereby increasing the complexity of processing required to derive position knowledge (Waldron and McGhee 1986). Important research in position estimation is still required however, particularly on knowledge based techniques for combining sensor information and handling uncertainty (Harmon 1987).

In addition to determining its position in space, and controlling its position as a function of perceived position, a mobile robot may have to autonomously plan safe paths and navigate towards a given goal if it is to be useful in performing complex tasks in unstructured and dynamic environments. Considerable work has been reported on the problem of robot path planning and navigation in known, static terrains. However, the problem of robot navigation in unknown or dynamic environments is currently much less advanced. A robot navigating in such an environment must concurrently, albeit

6 Dead reckoning is a technique where the relative position of a vehicle is tracked using an optical encoder or resolver to measure the precise rotation of the drive wheel. Position is calculated based on the number of wheel rotations, referenced to a starting point of motion. Wheel slippage and other sources of error limit the accuracy of dead reckoning such that the distance of travel is usually limited (Miller 1985).

incrementally, build a terrain map in real time using information of varying levels of resolution obtained from different sensors, and plan a safe path to any destination point. A number of sophisticated autonomous vehicle testbeds have already been developed which partially satisfy these requirements, but are not yet generalizable to practical task environments (Meystel 1988).

### 3.2 Construction Automation and Robotics Technology

Although industrial robot technology has largely developed to meet the needs of manufacturing operations, it is gradually being adapted to meet the unique requirements of construction operations. Because of the wide range of applications considered in this review, a useful distinction is made between light and heavy construction operations. Heavy construction operations are defined as those which typically involve earthmoving or transporting heavy and/or bulky objects over large distances. In building construction, for example, most operations involved in groundwork, substructure, and superstructure construction fall in this category. Light construction operations involve more conservative design requirements, particularly with respect to payload, reach, and the nature of the working environment. Such operations are, generally, constrained by the building, can be considered to be executed on a flat surface, and require manipulating smaller loads over shorter reaches. Spraypainting and drywall construction are representative examples.

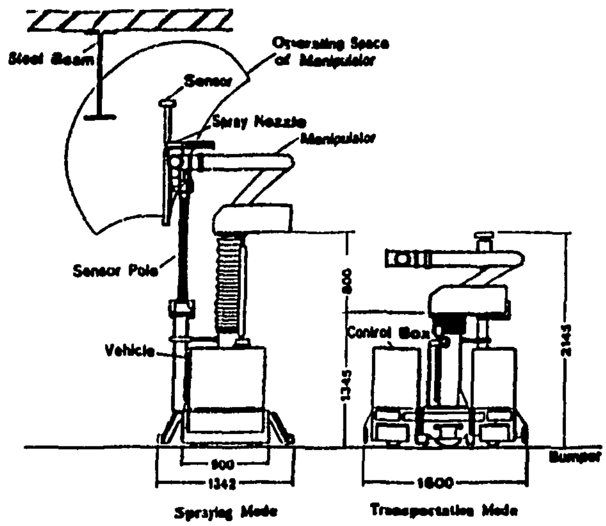
### 3.2.1 Mechanical Components and System Performance

1. Light Construction Operations

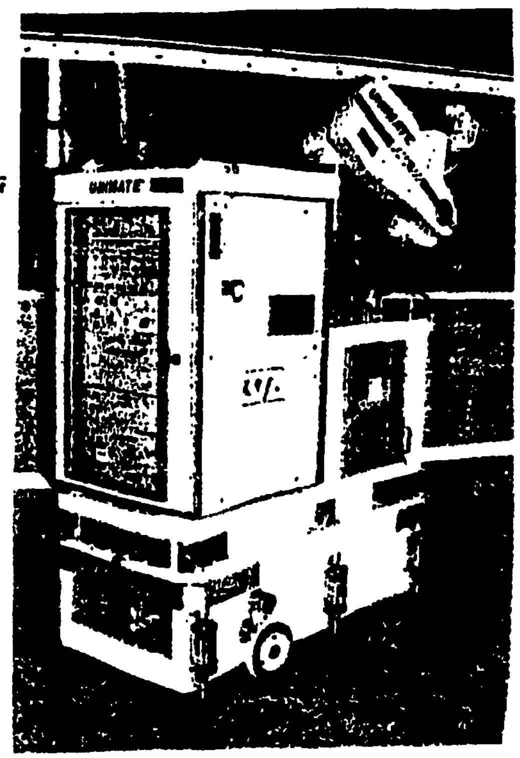
To date, most robots for light construction applications have been designed as modified industrial manipulators mounted on mobile platfoms, although a growing number are being developed based on entirely new designs. Experience with mechanical design of industrial manipulators suggests that the most efficient designs, in terms of both cost and performance, result when considering a narrower rather than a broader range of application (Seering and Scheiman 1985). A recent study at the Massachusetts Institute of Technology (MIT), whose purpose was to investigate the use of task-specific versus general-purpose robots, suggests that the same principle applies in building tasks (Demsetz 1989).

Examples of task-specific construction robots based on industrial manipulator designs are shown in Figure 3.5, and include a steel fireproofing robot, a ceiling painting robot, a proposed sandblasting robot. Examples of robots based on new manipulator configurations are shown in Figure 3.6, and include a concrete block placing robot, two ceiling panel positioning robots, and a robot for installing metal tracks and studs.

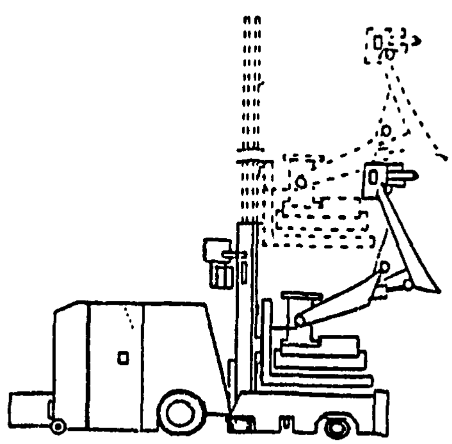
From the point of view of applications to light construction operations, the most important attributes of a robot manipulator's performance are payload capacity, reach, and most of all accuracy. Warszawski (1984) suggests that most "interior" (i.e., light) construction tasks can be accomplished with a payload capacity of an average worker, that is of approximately 10 to 30 kg, and a larger reach, of about 3 to 4 m. Surveys of robot capabilities indicate that most models have a lifting capacity in the under 40 kg




(b) Ceiling Painting Robot (I2)

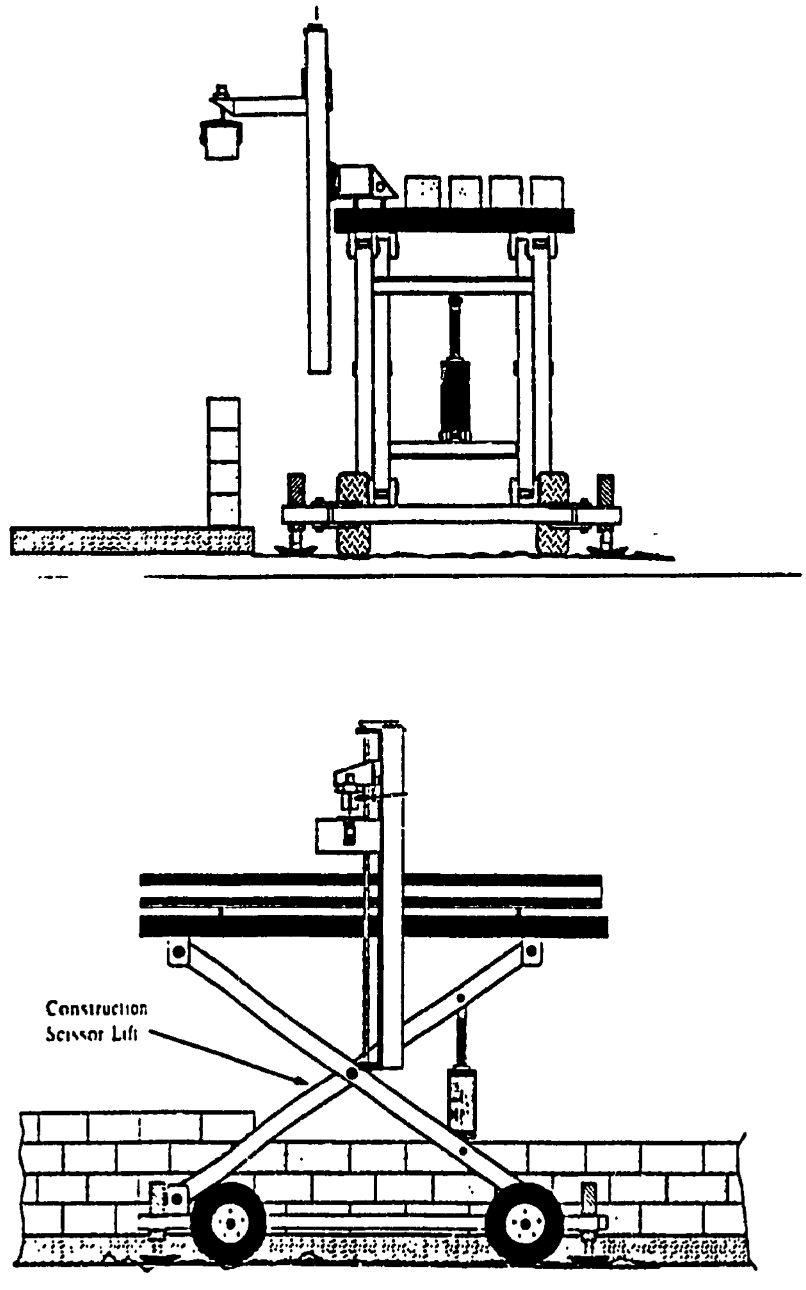


(a) Steel Fireproofing Robot (I3)



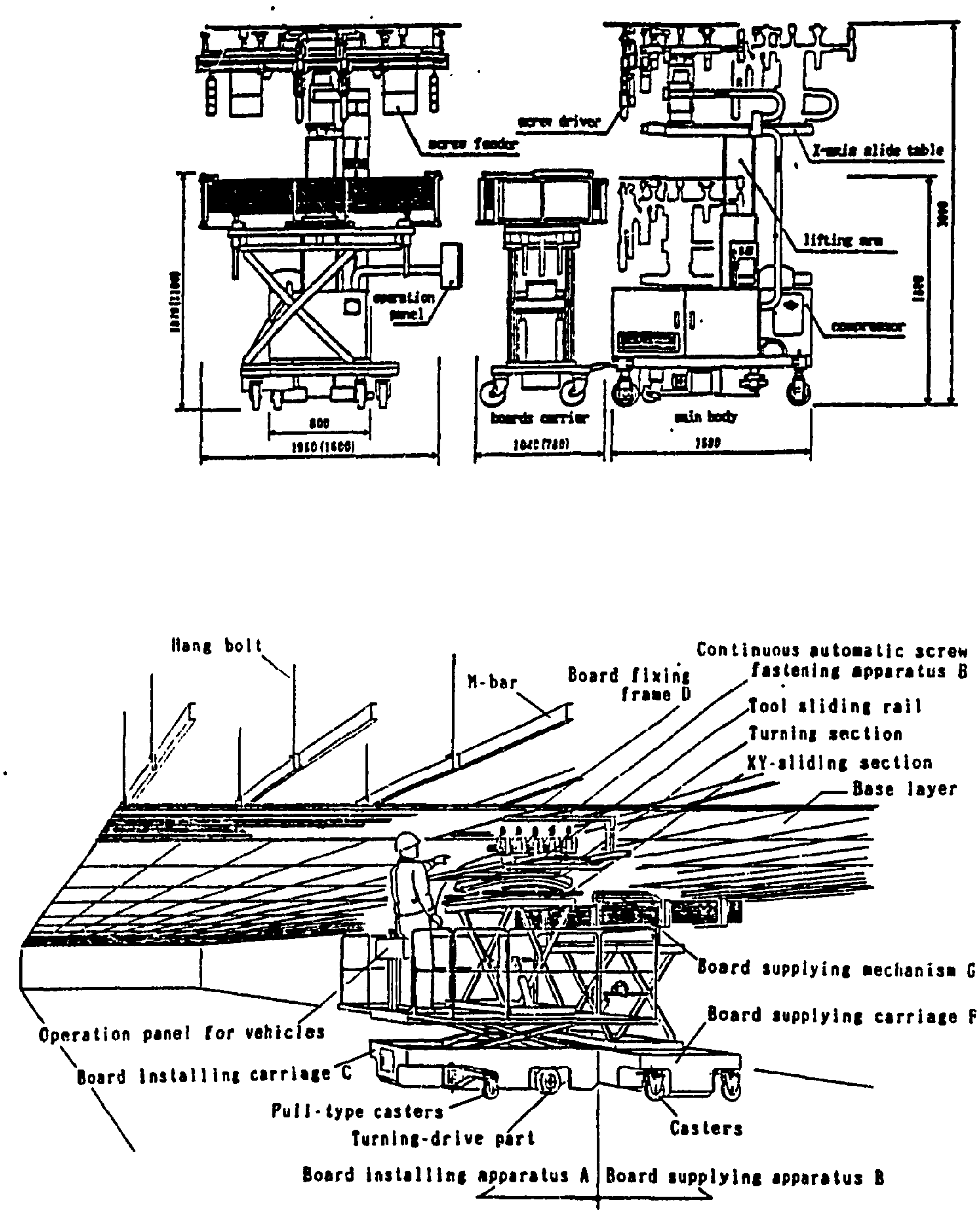
(c) Sandblasting Robot

Figure 3.5: Examples of Task-Specific Construction Robots for Light Construction Applications Based on Industrial Manipulators



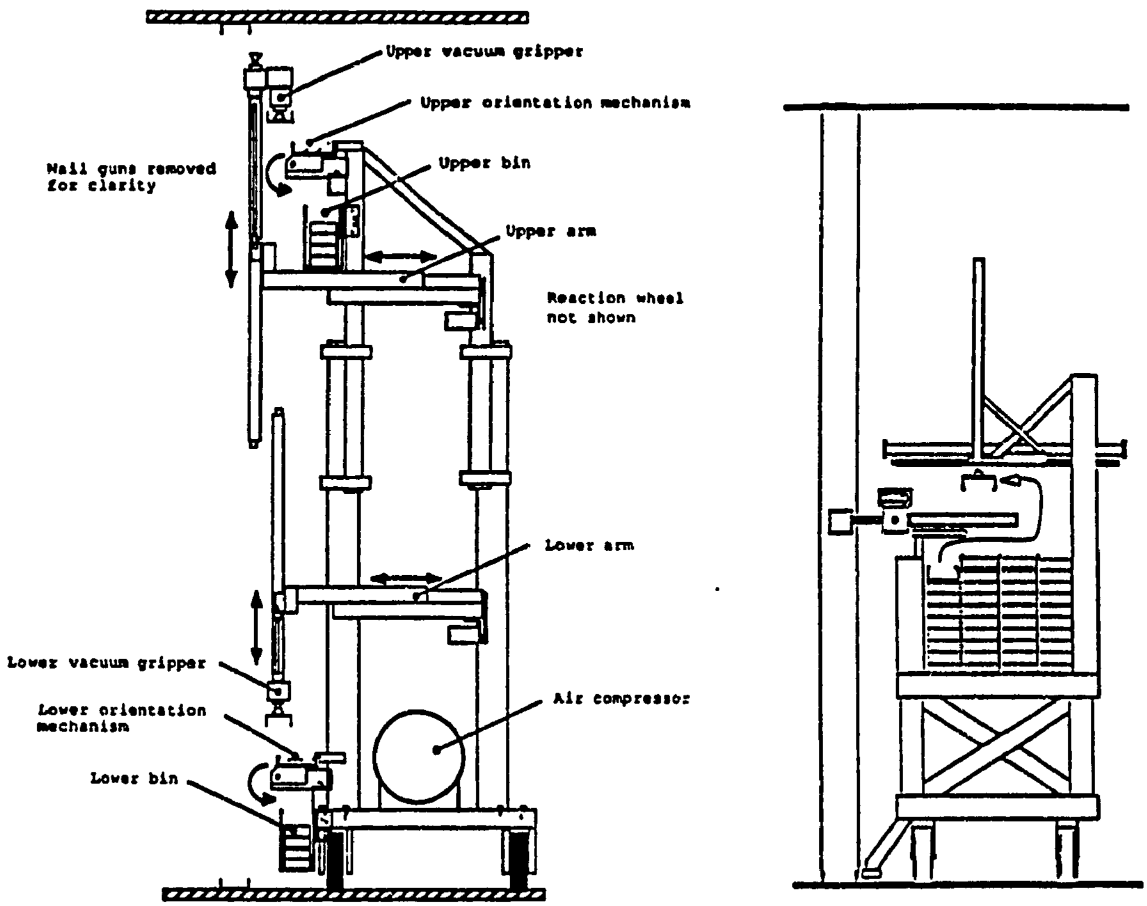

(a) Concrete Block Placing Robot (J2)

Figure 3.6: Examples of Task-Specific Construction Robots for Light Construction Applications Based on New Manipulator Design




(b) Ceiling Gypsum Board Installing Robots (H1)

**Figure 3.6: Examples of Task-Specific Construction Robots for Light Construction Applications Based on New Manipulator Design (cont'd)**




(c) Robots for Installing Metal Tracks (left) and Studs (right) (15)

Figure 3.6: Examples of Task-Specific Construction Robots for Light Construction Applications Based on New Manipulator Design (cont'd)

range (Fisher et al. 1992; Lewis et al. 1992). Typical of a large electric robot[7] would be a machine with a maximum payload of approximately 60 kg at a reach of 2.3 m (Walker 1987). Thus, although the payload capacity of current industrial robots is sufficient for most light construction applications, reach might have to be extended.

Closely related to reach and payload capacity, but a potentially more critical problem, is accuracy. In construction, since the same task is carried out many locations, the need to frequently reconfigure work parameters suggests that the capacity to program a robot using an existing CAD database holds much more potential than that of programming by physically guiding the manipulator. Accuracy, is, however, one of the most important problems in the performance of non-repetitive tasks programmed from a database (Day 1987; Paul 1983). While accuracies for industrial manipulators can range from ±100 mm to ±0.01 mm (Seering and Scheiman 1985), approaching the latter limit can only be achieved at great cost, by designing stiff structures which are manufactured to high tolerances and use precision mechanical components. The value of such equipment on a construction site would appear to be very limited. One possible solution to the accuracy problem is through the use of sensors. According to Paul (1983),

> A sensor controlled robot needs only enough absolute accuracy to be able to disambiguate features which are located by its sensors. This represents a far lower level of accuracy than that provided by today's robots. A decrease in robot accuracy requirements makes possible an increase in ruggedness and a decrease in both mass and energy inputs.

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7 Pneumatic actuators are not commonly used in industrial environments because of the difficulty in achieving precision placement and position control using compressed air; Hydraulic actuators are favorable with large loads, making them better suited for heavy construction applications.

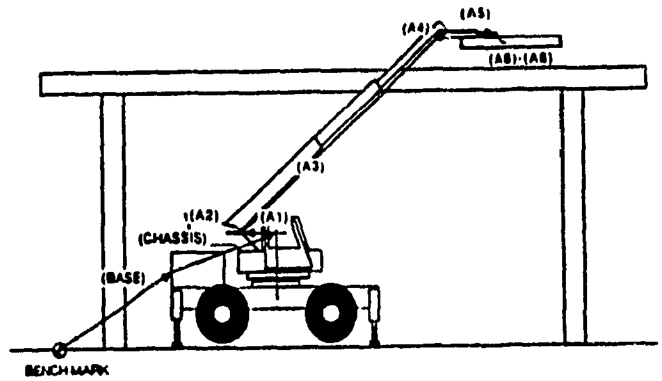
Any increase in ruggedness is highly desirable given the harsh operating environments exhibiting extremes of temperature, humidity, atmospheric contaminants, and shock and vibration. A reduction in the weight and size of the hardware is also extremely beneficial in satisfying possible constraints imposed by the structure under construction, especially since these constraints have been shown to impose significant limitations on construction robot design (Demsetz 1989).

2. Heavy Construction Operations

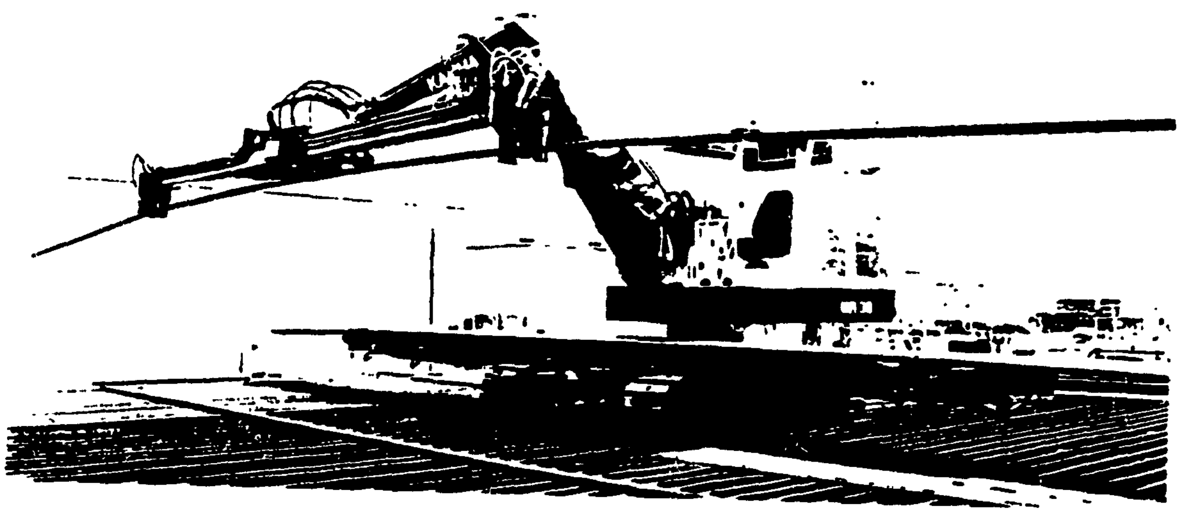
With respect to heavy construction operations, most applications of automation have been designed as modified construction equipment, while some have been developed based on entirely new designs. In the first case, automated equipment has retained many advantages of traditional construction equipment, such as ruggedness, a high pay-load-to-weight ratio, and large reach, while its utilization was either improved, such as in laser-guided grading (A2), or modified, such as the pipe manipulator and rebar placing robot shown in Figure 3.7. In the second case, automation is highly related to design approaches, requiring the building to be designed in such as way as to integrate the means for automated execution of its construction. Examples include the Horizontal Concrete Distributor shown in Figure 3.8, or automated building systems involving jacking up floors (B1) or placing exterior cladding (B3).

### 3.2.2 Programming and Control

For current applications of construction automation, three classes of control can generally be distinguished. At the lowest level of control, automation enables the extension,




(a) Robot Pipe Manipulator (F8)



(b) Rebar Placing Robot (E1)

Figure 3.7: Examples of Construction Automation and Robotics for Heavy Construction Applications Based on Traditional Construction Equipment

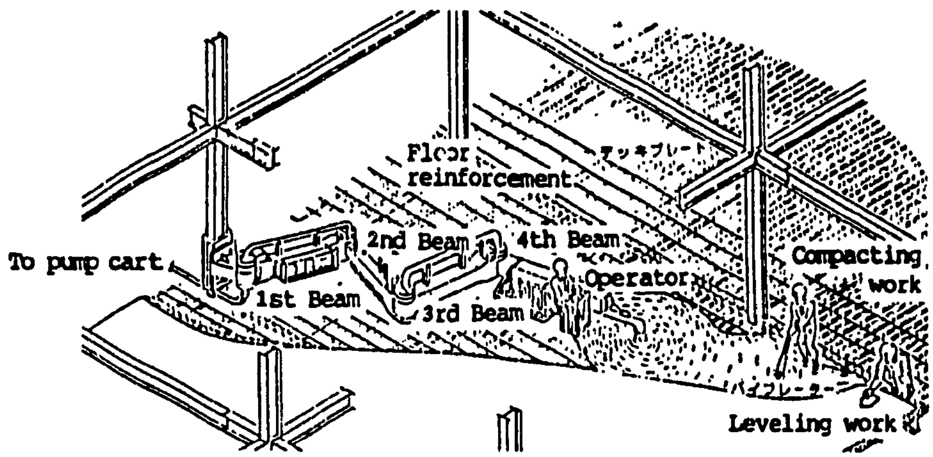
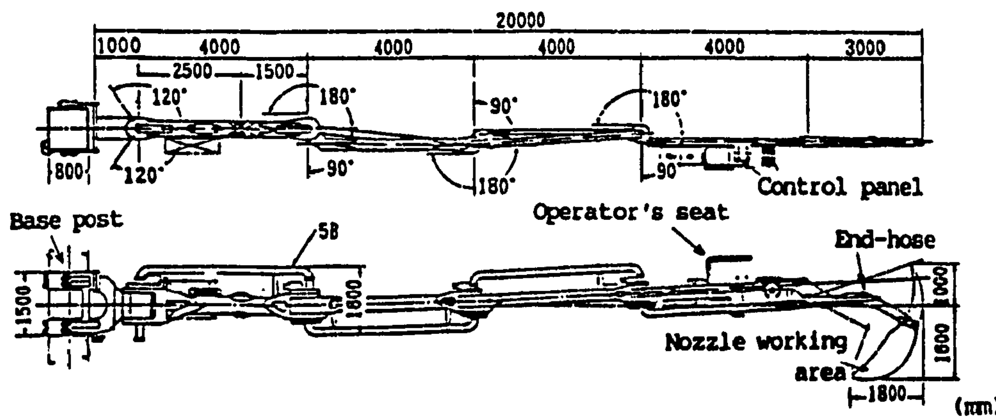



Fig. 2 Basic concept




Horizontal Concrete Distributor (C1)

Figure 3.8: Examples of Construction Automation and Robotics for Heavy Construction Applications Based on New Configurations

amplification, and/or optimization of human performance, leaving high-level control functions (planning, perception) to the human operator. At the second level, conventional programmed automation relies on positional control to perform repetitive tasks according to pre-specified instructions. At the highest level, intelligent automation relies on adaptive controls enabling the robot to sense, model, plan, and act to achieve goals without human intervention.

1. Light Construction Operations

Considerable efforts have been focused on applying conventional programmed automation to light construction operations. Concrete floor finishing (D4) became one of the first and most successful applications because there are no material handling requirements and the execution of the finishing function lends itself to simple positional control trough the use of wheel encoders and a gyrocompass. Positional control has also been successfully demonstrated for surface treatment operations involving application of fluid or semi-fluid substances. The ceiling painting robot (I2), for example, has demonstrated open loop control, where execution of the painting task is achieved solely through the control of the location of the robot in the room. In another application, spray fireproofing (I3), the robot and manipulator are manually positioned and, based on a library of beam sizes and spraying patterns, parameters are selected and work is executed.

Interior tasks which require positioning and attaching solid (i.e., discrete) objects have proven to be more difficult to automate. A number of positionally controlled robots have been developed which address only the function of positioning their payload. These include, for example, ceiling panel positioning robots (H2), which automatically place a panel using an X-Y horizontal table assisted by a compliant mechanism but leave the fastening to the worker, and the block placing robot (J2), which is capable of positioning specially manufactured concrete blocs in a staircase fashion (the blocks must then be surface bonded with mortar).

Very few positionally controlled robots have been developed which automate both the positioning and fastening of discrete objects. Examples include, robots which place and screw gypsum boards on ceilings (H1), and the robot for placing and fastening metal tracks on ceilings and floors (I5). In both cases, end-point feedback provides information about the position of the object being manipulated and the trajectory of the mobile base is predetermined.

These examples demonstrate that while conventional programmed automation can provide sufficient control capability to execute a narrow range of functions within certain simple and repetitive tasks, i.e. installing only rectangular ceiling panels in straight and unobstructed trajectories, it is not capable of providing the flexibility required for dealing with the variations encountered in normal field conditions. Since designing buildings and their components to the specifications and tolerances required for conventional programmed control is not possible, it is necessary that construction robots possess some capability for action in response to variable and evolving site conditions. Considerable research is being addressed in this direction, particularly on the issues of world modeling and task planning for specific domains and on CAD-based graphic simulation for robot programming (Garas 1992; Keriouz et al. 1988; Skibniewski 1992).

It has been suggested, however, that providing robots with the on-board computation and representation capabilities necessary for extracting and analyzing the information from their immediate working environment would require too sophisticated sensor and information processing technology and would not be sufficient to achieve typical construction goals (Slocum 1986; Whittaker 1986). Thus, another approach to intelligent automation has developed, which focuses on the development of databases that can store both as-designed and as-built information and serve as the central project controller (Demsetz 1990; Evans 1986; Slocum 1986).

For example, if a building were designed with built in control points, their precise measurement could provide reference coordinates for as-built data, and could serve as navigation beacons for guiding mobile equipment (Evans 1986). The central database would retain a global model of the site which could be updated by each robot with information about the completed task. The development of as-built databases would precipitate other improvements which would also support automation. For example, once as-built databases exist, communication with subcontractors could allow parts to be cut to fit, perhaps automatically, and be delivered to the site just before they were to be installed.

2. Heavy Construction Operations

To date, the level of control which has been implemented for automation of most heavy construction operations typically permits the extension, amplification, and/or optimization of human performance. This has been demonstrated through: 1) more efficient control of continuous process operations by sensing the work parameters between machine and materials which are beyond the operator's capacity, such as laser-guided grading (A2) and concrete leveling (D1); 2) work cycle sharing with repetitive operations alternatively under automated/human control, such as return-to-dig functions of excavators (A1); and 3) remote control of tasks such as excavation (A4), pipe manipulation (F8), and structural steel erection (F4).

Remote control, particularly for earthmoving equipment, has generated considerable interest because it is seen as a way of gradually introducing increasing levels of automation. However, while many examples of teleoperated excavators and bulldozers have been developed, their adoption by industry has mostly been limited to hazardous applications. In analyzing the performance of bulldozers through teleoperation, Singh and Skibniewski (1988) found that the risk of economic loss through lowered productivity was more inhibitive than the benefits of teleoperation. This indicates that further research is required to improve the performance of teleoperated systems.

Most other research efforts involving heavy construction operations are focused at the other end of the automation spectrum, i.e., intelligent automation. The topics of domain modeling and trajectory planning have by far been the major focus of most current research efforts, and excavation one of the most popular applications (Bernhold 1993; Garas 1992; Romero-Lois et al. 1989). For example, the robot excavator developed by CMU (A5) has demonstrated unmanned, adaptive control of pipe excavation in a laboratory excavation. The robot consists of a truck mounted four link backhoe which positions a six link manipulator at the end of which a supersonic air jet cutter dislodges soil without direct contact. Sonar-built surface and object depth maps are constructed, from which appropriate trajectories are generated and executed. University of Lancaster's robot excavator (A6) has demonstrated similar capabilities in the field using a traditional bucket instead of an air-jet.

### 3.2.3 Sensing

Currently the use of simple sensor systems is common for monitoring and control of internal and external functions of heavy construction equipment. In the former case applications include monitoring engine power and transmission output to maximize performance (A1). In the latter case, sensing systems allow real-time monitoring of work in progress and provide input to automatic control systems: in laser-guided grading (A2) and concrete screeding (D1) for example, laser receivers combined with electro-hydraulic feedback systems provide real-time blade elevation control.

The use of sensors is also very basic in positionally controlled robots developed for light construction applications. Their functions include initiation and termination of actions, position estimation, and choosing among alternatives. Concrete floor finishing robots (D4), for example, use relative position wheel encoders to provide information on distances traveled and a gyrocompass to determine heading. Simple proximity sensors are also used to avoid collisions. Robots designed for surface treatment operations, such as for spray fireproofing (I3) and painting (I2), have made use of different types of sensors: typically, short-range proximity sensors mounted on the manipulator that enable the arm to position itself closely to the work surface; light sensors that detect signals emitted from Light Emitting Diodes (LEDs) mounted on the corners of the work area, and, by triangulation, detect the position of the robot with respect to the work surface. The robot for positioning and fastening metal studs on ceilings and floors (I5), makes use of on-off switches and array of photodiodes used to detect a rotating laser beam for providing end-point feedback.

The key feature which will make field applications of automated or robotic equipment truly effective will be their capacity to obtain and understand information about their working environment. Advances in sensor technologies, such as magnetic vision for detecting reinforcing bars, sonar sensing for room mapping, subsurface mapping for locating underground objects, and smart sensors which incorporate local signal processing capability, are expected to generate many new applications (Evans 1986; Paulson 1985). Promising new areas are being investigated such as macrometrology, making precision measurement of large structures, and photogrammery, extracting reliable information about objects and their environment from photographic images (Evans 1986). Some of the most important problems yet to be resolved involve integrating data from multiple sensors to construct and update a world model of the robot's working environment (Chamberland et al 1992; Keriouz et al. 1988; Schmitt and Juge-Hubert 1990), structuring the interaction of sensory processing in hierarchical control systems (Albus 1984), and the automated collection of information from work in progress for downloading to a central project controller (Demsetz 1990; Paulson 1985).

### 3.2.4 Mobility

Unlike applications of automation in heavy construction operations that rely on traditional construction equipment, the provision of general mobility for applications in light construction operations is a considerable challenge. It appears that many construction robots for such applications can be expected to be rugged vehicle-manipulator combinations, whose working environment changes with the progress of work, and whose travelling surface may be uneven, unlevel, or unstable.

Many tasks, such as steel fireproofing (I3), ceiling painting (I2), concrete block laying (J2), and metal stud positioning and fastening (I5) have been implemented as vehicle manipulator combinations. The first two represent typical industrial robots mounted on mobile platforms with articulated steering. Of these, the first follows a floor-laid guidewire and the second uses a combination of 24 ultrasonic sensors for absolute positioning and wheel encoders for relative position measurement. Additionally, the first robot uses end-point feedback to control the end-effector position, whereas the second relies solely on the positioning of the mobile base to control the end-effector. The concrete block laying and metal stud positioning robots represent new manipulator configurations mounted on a construction scissor lift in the former case, and on a custom built platform in the latter case. Both have articulated steering and use a combination of relative position sensors for platform positioning and end-point feedback for end-effector control.

Although these applications represent important developments, considerable research still needs to be conducted on the relationship between mobile platforms and the manipulation devices which may be mounted on them (Waldron 1985). Particularly important are issues related to the accuracy of vehicle-manipulator combinations with articulated steering, the control of vertical displacement due to vibration, and the incorporation of platform mechanics in manipulation algorithms. However, most construction automation research directed at mobility is focused on real-time position measurement systems for equipment navigation. In particular, absolute position sensing technologies such as Global Positioning Systems based on satellite or ground fixed locations, laser-based positioning systems, and map referencing systems are at the experimental stage (Singh and Skibniewski 1988; Skibniewski 1992).

### 3.3 Summary

This review has shown that robotics has largely developed to meet the needs of manufacturing operations, in which the robot performs repetitive tasks at a single location under conditions which do not usually vary. The following factors represent the main technological areas where significant advances must be made before automation and robotics can lead to less constrained applications on construction sites.

1. The ability to program a robot independently of its working location.

   The main problem with programming frequently reconfigured tasks, such as those found in construction, is that it is not yet possible to separate the description of the procedure required to execute a task from the location of the task. This would allow a robot to be programmed away from the site, based on a CAD description of the task.

2. The ability to create and update models of the environment based on sensor information.

   Since it is impossible to completely specify, a priori, all the information about the working environment, construction robots will rely on sensor systems that are much more advanced than those generally found in industrial robots. This requires sophisticated sensor fusion and domain modeling capabilities.

3. The need for a central project control system.

   Since providing individual robots with the computational and representational capabilities required to achieve typical construction goals may not be feasible, more effective levels of automation could be achieved by a central project control system which would contain as-designed and as-built information and would enable manual and automated equipment to exchange information automatically and work interactively.

4. The mechanics and control of vehicle-manipulator combinations

   This is an area which has received little attention in industrial automation research but which is critical to construction because most applications of automation and robotics in light construction operations are expected to be vehicle-manipulator combinations.

5. Design for automated construction

   Lessons from manufacturing have shown that the greatest benefits from automation will occur when the building delivery process adopts methods which produce designs appropriate for automated construction. In lieu of such an objective, the focus is on design of reduced cost components rather than components that can be automatically assembled.

# CHAPTER IV

# RESEARCH METHODOLOGY

A fundamental tenet of this thesis is that contractors can gain immediate benefits from automation by using currently available or soon to be developed automated or robotic equipment. Determining how automation can be implemented to achieve this goal forms one of the supporting objectives of this thesis. The methodology used in achieving this objective, the selection of an operation for a case study, and the factors considered in the field investigation, are presented in this chapter.

## 4.1 General Methodology

For the purpose of this study, a construction operation is defined as a functionally grouped set of concurrent and/or sequential tasks. In order to achieve operation objectives of cost, time, and quality, contractors will need to integrate tasks executed using conventional manual, partially automated, and fully automated work strategies in such a way as to allow the benefits of each to be fully realized. The proposed methodology for analyzing the planning of such an operation is presented in Figure 4.1.

Before commencing, alternative methods for performing the operation are defined considering appropriate combinations of manual and automated equipment. The analysis can be viewed as a three stage process, consisting of operational analysis, simulation, and economic analysis. In the first stage, operational characteristics of each alternative are determined based on task, quality, and productivity analyses. The conventional manual

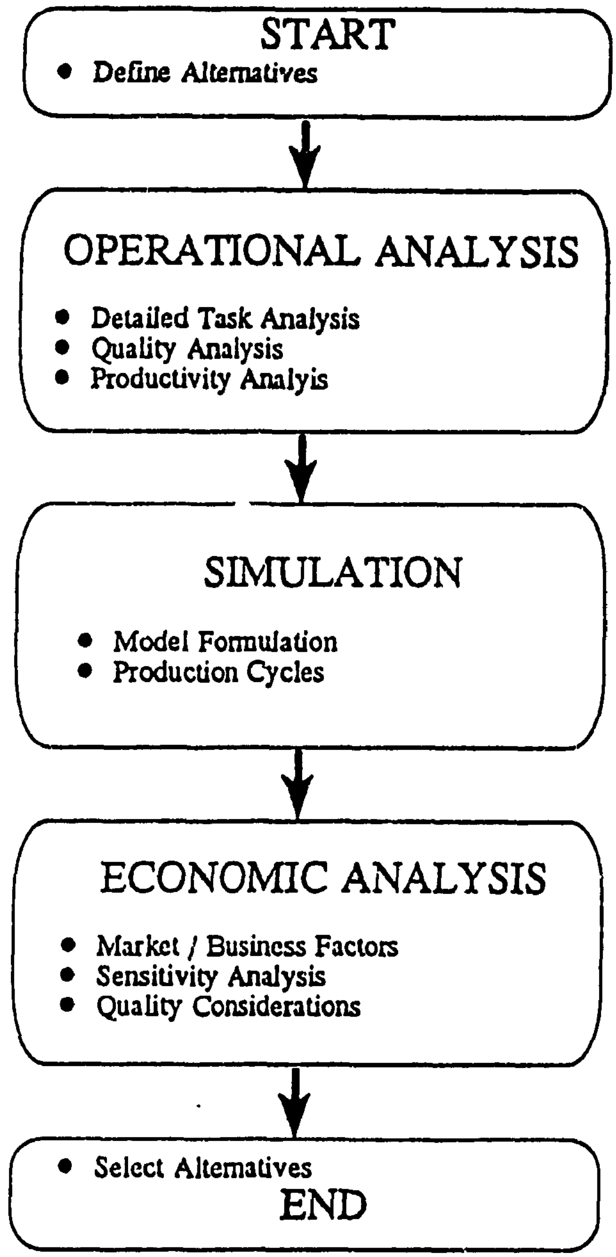



Figure 4.1: Methodology for Analyzing the Implementation of Automation in Building Construction Operations

construction operation is first defined by identifying constituent work tasks and the interactions among them. Unlike many manufacturing applications where the precise production process required to manufacture a product is well established and can be considered as a rigid programme to be executed under known conditions, the methods and practices used to construct buildings and their components may vary from region to region and between contractor: thus, a detailed analysis of each task is required in order to identify local work practices, methods, and equipment. A similar analysis is performed for each task where automation is being considered.

Since the quality improvement which can result from automation is expected to be an important benefit in construction, a quality analysis is performed. Factors that have the greatest influence on the quality of the manually constructed product are identified through task analysis and are compared with the quality-influencing factors of the automated tasks to determine the attainable level quality for each alternative.

For each alternative, resource units and durations are identified, or in the case of a new technology, estimated, and a productivity analysis is performed. Compatibility between sequential/concurrent tasks is verified and potential bottlenecks are identified by exploring the ability to modify individual task productivities.

In the second stage, a computer model of the operation is developed and is used to simulate the various alternatives. Computer simulation presents an excellent tool to quantify and compare attainable production levels using different technologies, particularly ones for which prior experience is limited. The factors which are generally considered to be basic to the definition of any meaningful model of a construction operation, i.e., the elemental work tasks, individual resource units associated with each task, and the resource units flow rates through the work tasks (Halpin and Woodhead 1976), have all been identified in the previous stage. Thus, once a simulation package is selected, a model can be developed and production cycles determined for each alternative. These production cycles are then used, in the third stage, as the basis for economic analysis. In this stage, business and market factors are identified and an economic analysis is performed to compare the cost of each alternative and to identify the factors which will influence the decision to automate a specific task.

### 4.2 Selection of Case Study Operation and Definition of Levels of Automation

Since the use of automated and robotic equipment on construction sites is still very limited, the selection of a case study operation was found to be a difficult task. The most important consideration in the selection process was that the operation allow the full investigation of construction automation related concepts developed in this thesis, as well as the performance of detailed task, productivity, and economic analyses, with a minimum of speculation and reasonable accuracy. In light of this, the operation selected for analysis was the construction of concrete slabs on grade.

Slab-on-grade construction follows the basic functional steps of any concreting operation, namely, production of the concrete mix, delivery to worksite, transfer to workface, and placement and treatment. Unlike many concreting operations however, slab-on-grade construction is a relatively simple operation composed of sequential, repetitive work tasks performed on an easily accessible, flat surface, thus making it amenable to automation. In fact, a wide range of resources can be combined to perform the different tasks, including manual labour using mechanized equipment, semi-automated placing using laser-guided screeding machines (D1), and automated finishing using robotic floor finishers (D4). Although, of the automation technologies developed for this application, only laser-guided screeding equipment is currently available and in use in Canada, it was felt that the implementation of various levels of automation could nevertheless be effectively addressed.

### 4.2.1 Background

Although concrete slabs on grade can be found in all types of buildings, it is in industrial and commercial facilities that their construction represents a most challenging undertaking, as it can involve both large surfaces, over a 100,000 $m^2$ in some cases, and stringent performance requirements. Parking lots and pavements are also technically slabs on grade, but are not included in this analysis.

In virtually all industrial applications, the slab-on-grade represents the finished surface upon which daily work is carried out, and therefore has both functional and aesthetic value. Its serviceability is entirely dependent on achieving a hard, durable, flat and level surface which is free of cracks. Yet concrete slabs on grade have for many years been the source of owners' and plant managers' displeasure. In the early 1960's, slabs on grade represented a significant proportion of building defect problems in both the United States (Ytterberg 1961) and Canada (Dickens 1961). These were comparatively rarely due to settlement or other major structural causes, but were more commonly due to poor performance of the surface. Today, experience suggests that floor surface quality varies tremendously, regardless of the construction method, and that floors still commonly experience problems, perhaps even more than 25 years ago (Garber 1988; Ytterberg 1987).

Additionally, in recent years, the changing needs of owners have increased the pressure on contractors for more cost effective and rapid construction, and, paradoxically, for unprecedented accuracy in floor slab construction. Once an industrial building is roofed and enclosed, the floor often becomes the most critical item, as it is required for the construction of interior partitions or the installation of equipment: rapid construction and early use are therefore always stressed in order to meet schedule constraints. However, the floors that owners are demanding are being required to meet increasingly stringent performance requirements, as warehouses and distribution facilities have themselves been revolutionized by developments in automation, such as AGVs and computer controlled very-narrow-aisle/ high-bay storage and retrieval systems, which require extremely precise floor surface tolerances.

### 4.2.2 Levels of Automation

Faced with a rigorous, labour intensive construction process exhibiting common quality problems and subject to increasingly stringent requirements, slab-on-grade contractors need the productivity and quality improvements afforded by automation. The technologies which have been developed for this application include:

1. Semi-automated placing equipment:

The automation of concrete placing through laser-guided screeding is an example of the growing use of laser technology in construction (DeBoer 1991; Paulson 1985). A number of approaches to laser-guided screeding have been developed, namely, truss-type rail-mounted (Nomura et al 1989; Yoshitake et al. 1991), ski-mounted (Smith 1991), and retractable vehicle-mounted screeds (Fling 1987). The latter approach offers significant advantages over the former approaches in that it allows wide pour widths, therefore reducing the need for rails, forms, or other screed guides.

The laser-guided screeding equipment considered in the present study, shown in Figure 4.2, is a four-wheel drive vehicle supporting a 6 m (20 ft) long telescoping boom, at the end of which is attached a 3.7 m (12 ft) wide carriage which can be raised or lowered by a pair of hydraulic masts. The carriage houses a 230 mm (9 in.) diameter auger which uniformly distributes the concrete, and a vibrating straightedge which strikes off the surface.

A self-leveling rotating laser is set up outside the work area, defining a reference plane parallel to the design grade. Laser receptors are permanently mounted on the machine at each end of the carriage on the hydraulic masts. The point at which the laser beam strikes the receptors on the hydraulic masts is transmitted to a microprocessor, which calculates the difference between the desired and actual carriage elevation. As the boom is retracted, the microprocessor commands the hydraulic control system to raise or lower the masts at a frequency of five times a second, thus maintaining the proper carriage elevation.

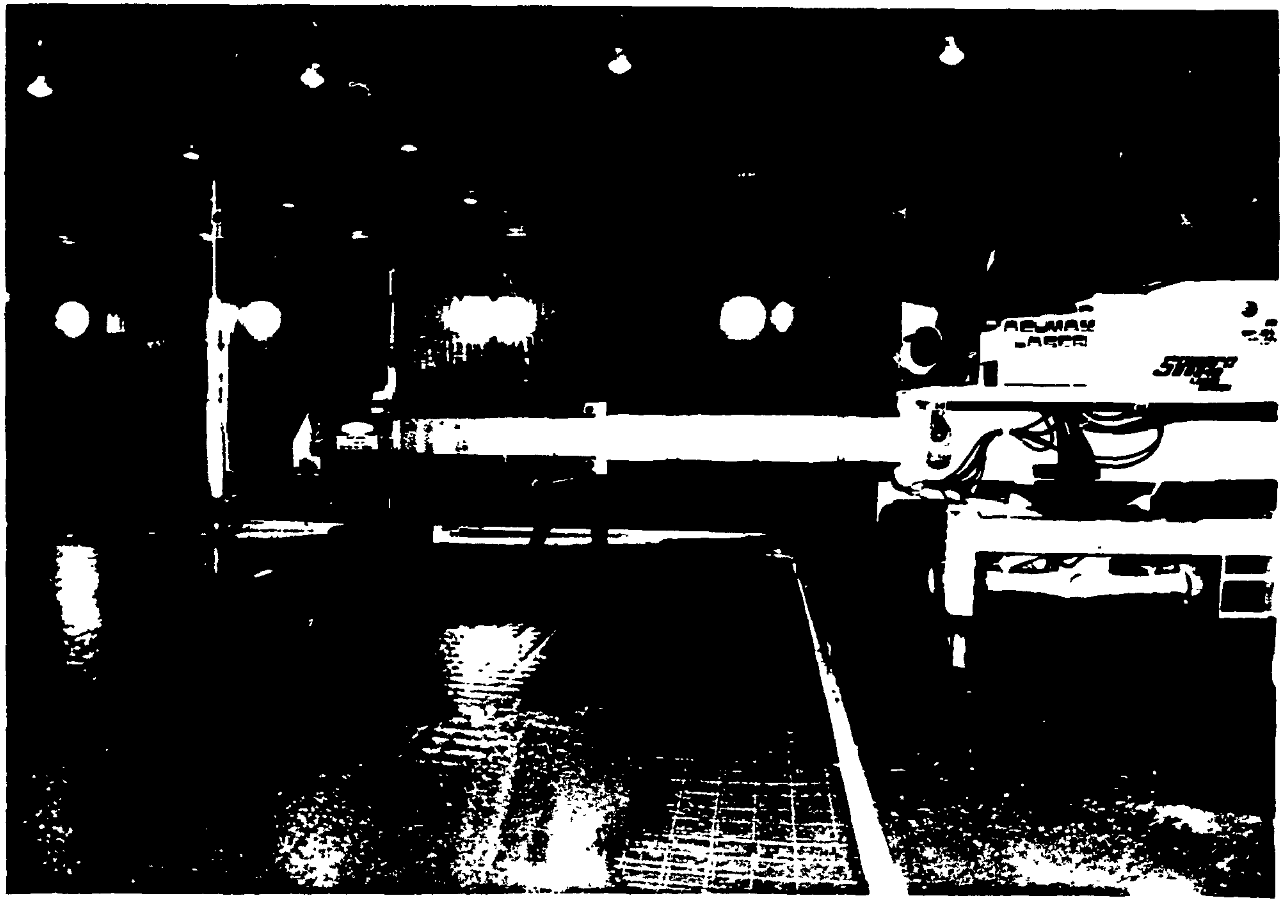


Figure 4.2: Laser-Guided Screeding Machine Used in Study

Although automatic control can always be overridden by the operator, use of the laser-guided screeder is not recommended where there are many obstructions. Also, the equipment cannot be used on elevated slabs or slabs with sloping surfaces.

2. Robotic floor finishers:

The automation of concrete floor finishing has been an area of great interest to leading Japanese contractors since their initial involvement with construction robotics. In 1984, a first attempt at developing a floor finishing robot produced a device which imitated the action of a human operator finishing a slab (see Figure 4.3). The device, which swept a trowel assembly back and forth much like a human finisher handles a power trowel, proved to be bulky, awkward, and difficult to program (Arai et al 1988). More recent attempts have refined the design, producing a family of similar devices differing mostly in their degree of autonomy (see Figure 4.4). These robots, although used in Japan, are not yet commercially available abroad. Table 4.1 compares the characteristics of the different types of robotic floor finisher shown in Figure 4.4 with those of a standard mechanical power trowel.

The robots typically consists of twin or triple trowel assemblies rotating around or behind a motorized unit travelling on rollers. As the unit advances, the trowels finish the surface, thereby erasing roller tracks. All four models presented in Table 4.1 can be teleoperated, and last three models can also be programmed. Programming consists of entering the dimensions of the area to be finished, the overlap width, the initial travel direction, and setting the operating parameters such as travel speed and blade angle. The on-board micro-computer then calculates the travelling pattern such that the entire area is covered by a series of transversal passes.

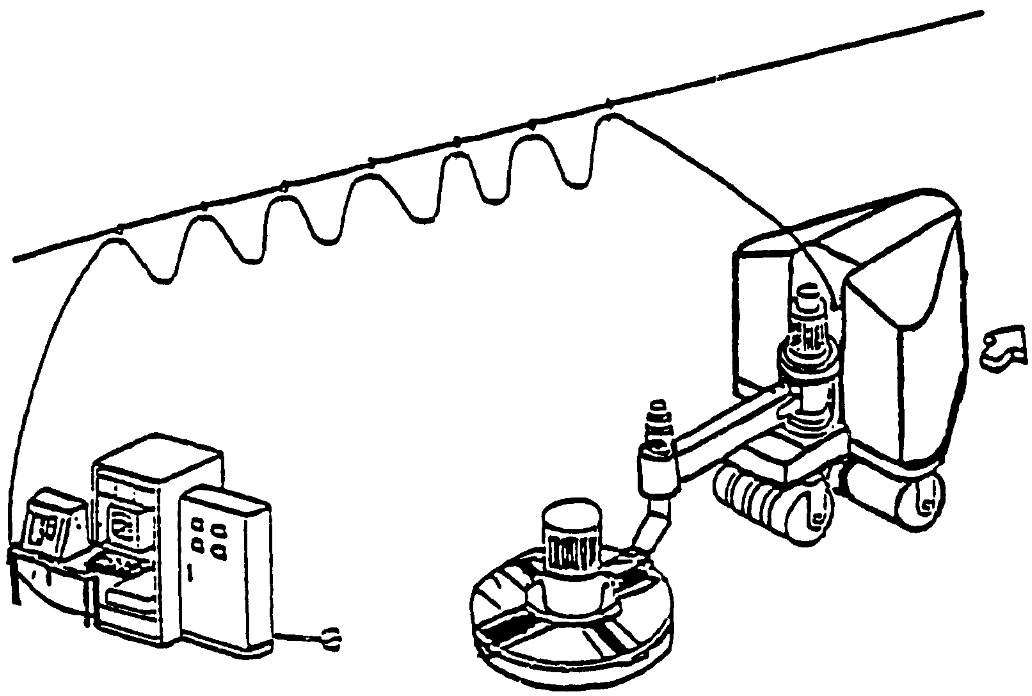
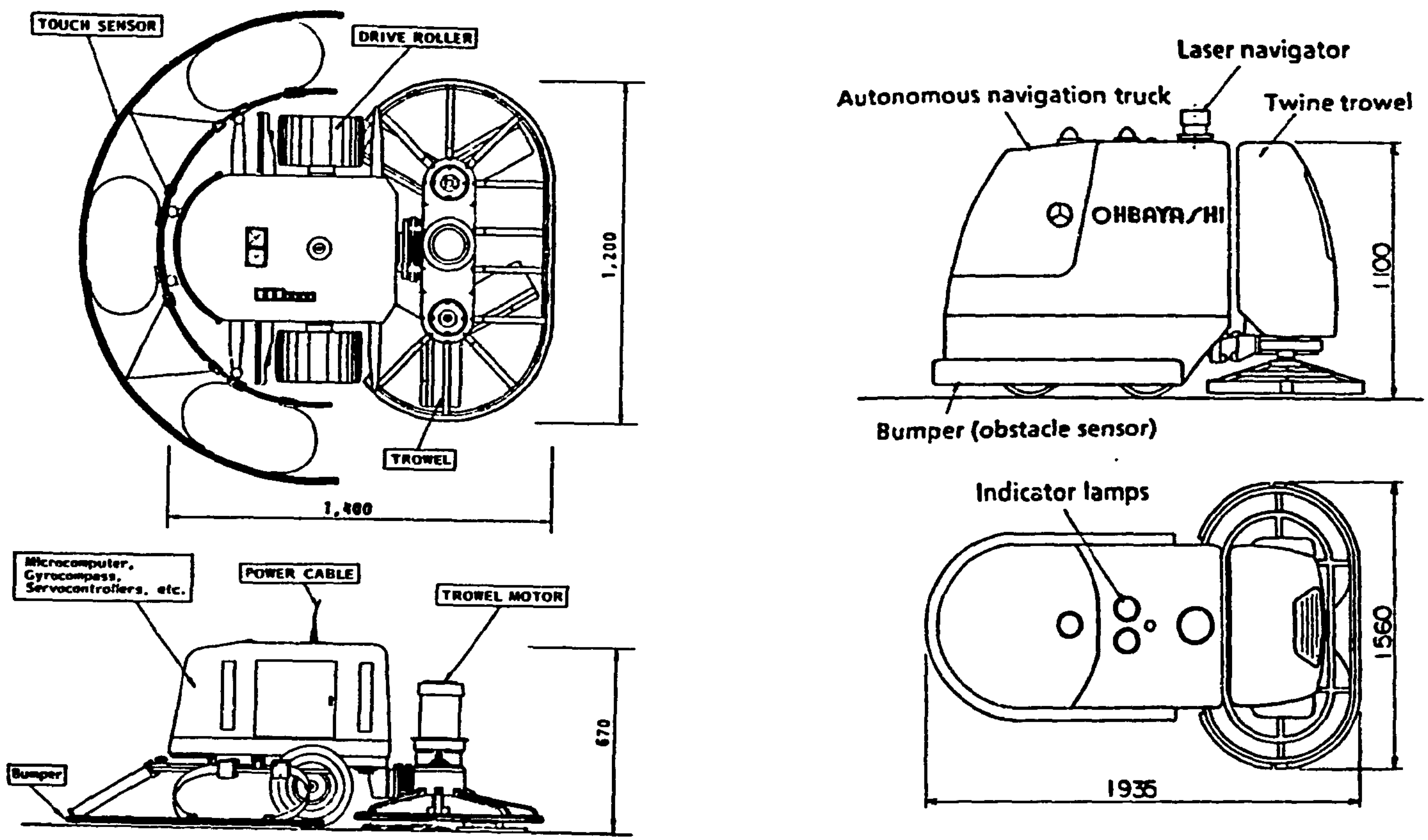


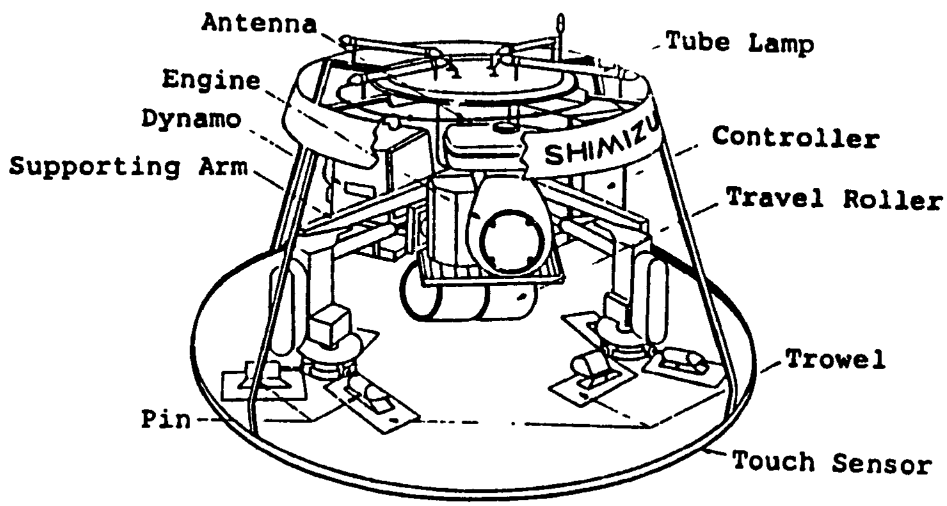
Figure 4.3: First Generation Concrete Floor Finishing Robot (Arai et al. 1988)



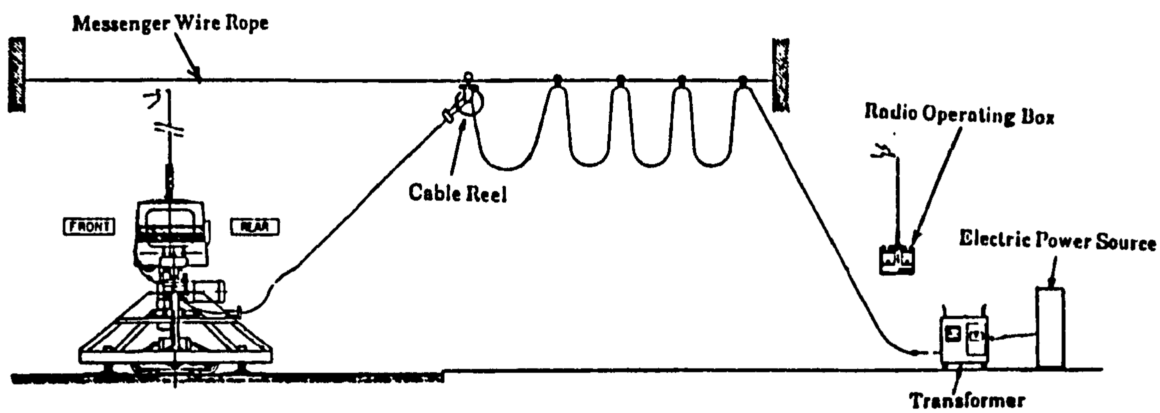

(a) MARK II (D4)

(b) Ohbayashi Robot (D4)

Figure 4.4: Second Generation Concrete Floor Finishing Robots




(c) FLATKN (D4)




(d) SURFROBO (D4)

Figure 4.4: Second Generation Concrete Floor Finishing Robots (Cont'd)

| Type | | Characteristics | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Name | Developer | Weight (kg) | Travel Speed (m/min) | Engine rpm | Lapping Width (m) | Production Rate ($m^2/hr$) | Control | Trowel Assembly | Power | Guidance/ Navigation | Obstacle Avoidance | Ref[1]. |
| Power Trowel | Bartell, Honda, other equipment suppliers | 70 | n/a | 50-135 | 0.91 | 230-280 | Manual | 1x4 blades | Gasoline engine | Manual | Manual | 60 |
| Flatkn | Shimizu | 300 | 0-10 | 70-100 | 2.30 | 400-800 | Teleoperated | 3x3 blades around unit | Self-contained gasoline engine & Generator | Manual | Immediate stop on contact | 25 |
| Mark II | Kajima | 185 | 0-13 | n/r | 1.20 | 450-700 | Teleoperated Preprogrammed | 2x3 blades behind unit | Electrical through unbillical cable | (Relative) Gyrocompass & Encoder | Adaptive | 28 |
| Surf Robo | Takenaka | 185 | 0-12 | 0-35 | 2.14 | 300 | Teleoperated Preprogrammed | 2x4 blades around unit | Electrical through unbillical cable | (Relative) Gyrocompass & Encoder | Touch Sensor | 27 |
| n/r | Ohbayashi | n/r | 0-10 | n/r | 1.56 | 500 | Teleoperated Preprogrammed | 2x3 blades behind unit | Self-contained | (Relative) Encoder & (absolute) Laser | Touch Sensor | 26 |

1: References provided in Appendix A
n/a: not available
n/r: not reported

Table 4.1: Characteristics of Mechanical and Robotic Floor finishers

Since none of the models follow a fixed path or guidewire, a guidance system is necessary. For the first model in Table 4.1 this is accomplished by manual remote control. As previously discussed, reliable free-range guidance is presently achievable by combining both relative position sensors, which provide continuous positional knowledge but are subject to cumulative errors, and absolute position sensors, which provide positional knowledge with respect to external reference points. Of the programmable units in Table 4.1, only the last model combines both relative and absolute sensors: its developer indicates a positioning accuracy of ± 5 cm, and a heading accuracy of ± 0.5 deg for this unit (Nishide et al. 1988). The remaining programmable units use only relative position sensors but do not report any positional accuracy data.

Given these technologies, four levels of automation need to be considered, namely;

1. Conventional manual construction, consisting of Manual Placing and Manual Finishing (MP/MF),
2. automation of placing alone, consisting of Semi-Automated Placing and Manual Finishing (SAP/MF),
3. automation of finishing alone, consisting of Manual Placing and Robotic Finishing (MP/RF),
4. automation of the entire operation, consisting of Semi-Automated Placing and Robotic Finishing (SAP/RF).

## 4.3 Field Investigation

The information required to conduct this analysis was gathered directly from experts in the field, i.e., local concrete contractors who specialize exclusively in placing and finishing concrete slabs and who have the experience and know-how required to evaluate both current practices and the potential of new technologies. Five Montreal area contractors specializing in concrete slab construction agreed to participate in the study: they ranged from a small company with 10 employees, an annual operating revenue of 0.5M \$, and an annual volume of work of 83,656 $m^2$ (900,000 $ft^2$), to perhaps the largest cement finishing contractor in Quebec, with 25 employees, an annual operating revenue of 1.5M \$, and an annual volume of work of 371,802 $m^2$ (4M $ft^2$). Included among the study's participants is the first and only contractor to use a laser-guided screeding machine in the province of Quebec. The participants' profile is summarized in Table 4.2.

A two step procedure was used, consisting of structured interviews followed by site observations of task performance. This method was selected because;

1. it was felt that direct site observations alone would not provide the best method for obtaining representative productivity information because of the large number of productivity-affecting variables which cannot be controlled (type of concrete and slab, working conditions, site location, etc..), and the large number of samples which would be required

| Contractor | Annual Operating Revenues (M $) | Employees (total/site) | Annual Production Volume ($m^2$) |
|---|---|---|---|
| A | 1.5 | 25/20 | 371,802 |
| B | 1.1 | 23/22 | 185,901 |
| C | 1.0 | 22/18 | 232,377 |
| D | 0.865 | 15/12 | 171,959 |
| E | 0.5 | 10/9 | 83,656 |

Table 4.2: Profile Summary of Study Participants

2. since one of the technologies to be evaluated is not yet in use and contractors have very little experience with automation, it was necessary for the researcher to provide information to the contractor on which to base his evaluation. Thus, while a questionnaire was designed as a guide to collect the same information from every contractor, the interview allowed for exploratory responses emphasizing the experience which is unique to each.

Through the structured interviews, general construction practices were identified including breakdown of work tasks, pour sizes and placement widths, tools and techniques used, and quality assurance and control procedures. Information was obtained about crew size and composition, and work scheduling and duration, for the placing and finishing of a standard concrete mix ($f_c$=24 Mpa, slump=125 mm), with welded wire fabric nominal reinforcement, under ideal ambient conditions (T=21°C, RH=50%), for different daily pour sizes. Actual operating and maintenance costs were also obtained for both manual placing and finishing and semi-automated placing.

Information on cement floor finishing robots, in the absence of actual data on their use, was obtained through published reports and discussions with Japanese contractors, and has been reported in a previous study (Moselhi et al. 1992). In order to obtain the best possible understanding of the use of the robots, contractors were shown videotapes of floor finishing robots, and were asked to provide their views on the perceived advantages and disadvantages of their use. Since the construction industry has very little experience with automation, information was also obtained regarding the participant's receptivity to automation and robotics.

For each participant, three sites were visited, enabling firsthand observation of concreting crews and working practices. The sites were chosen to reflect different uses, were of different size and shape, and were visited over a one year period under different climatic conditions. Table 4.3 summarizes the characteristics of the different sites.

| Total Job Size (m²) | Use | Thickness (mm) | Slump (mm) | Strength (Mpa) | Outside Temp. (c°) | Construction Method |
|---|---|---|---|---|---|---|
| 483 | residential | 100 | 130 | 24 | 7 | wide pour/ manual |
| 558 | commercial | 150 | 130 | 24 | 26 | wide pour/ manual |
| 1,162 | residential | 100 | 125 | 20 | 5 | wide pour/ manual |
| 1,673 | runway | 225 | 100 | 32 | 17 | wide pour/ manual |
| 2,110 | commercial | 125 | 125 | 28 | 15 | wide pour/ laser screed |
| 2,249 | industrial | 130 | 130 | 24 | -2 | wide pour/ manual |
| 2,789 | industrial | 130 | 130 | 24 | 10 | wide pour/ manual |
| 3,002 | commercial | 130 | 130 | 24 | 21 | wide pour/ manual |
| 3,095 | commercial | 130 | 130 | 24 | 24 | wide pour/ manual |
| 6,042 | industrial | 130 | 125 | 24 | 22 | wide pour/ manual |
| 7,808 | industrial | 125 | 125 | 24 | 11 | wide pour/ manual |
| 7,900 | industrial | 130 | 125 | 24 | -5 | wide pour/ manual |
| 9,016 | industrial | 130 to 225 | 125 | 24 | 25 | wide pour/ manual |
| 11,154 | industrial | 130 | 100 | 28 | 15 | wide pour/ laser screed |
| 41,827 | industrial | 130 to 200 | 150 | 28 | -12 | wide pour/ laser screed |

Table 4.3: Summary of Construction Sites Visited

# CHAPTER V

# CASE STUDY:

# AUTOMATION OF CONCRETE SLAB ON GRADE CONSTRUCTION

In this chapter, the implementation of automation is addressed by considering the automation of concrete slab-on-grade construction through semi-automated concrete placing and robotic floor finishing, implemented either separately or jointly. A brief review of design principles, construction practices, and quality considerations is first presented. In following sections, according to the methodology described in Chapter 4, operational analysis, simulation, and economic analysis are performed. A summary of the methodology and conclusions regarding factors to consider in implementing automation are presented in the final section.

## 5.1 Design, Construction, And Quality Considerations

Slabs on grade may be exposed or enclosed, monolithic (single course) or double course, made of plain, reinforced, or prestressed concrete, and the reinforcing or prestressing may be provided for structural loading, or to control the effects of shrinkage and temperature variation. For the purpose of this analysis, slab on grade refers to a non-structural, monolithic slab, continuously supported by a flat and uniform, load bearing subgrade (typically compacted gravel), constructed in an enclosed but non climate-controlled space (i.e., subject to external temperature and humidity variations). It is believed that this type of slab, illustrated in Figure 5.1, represents the majority of today's installations.

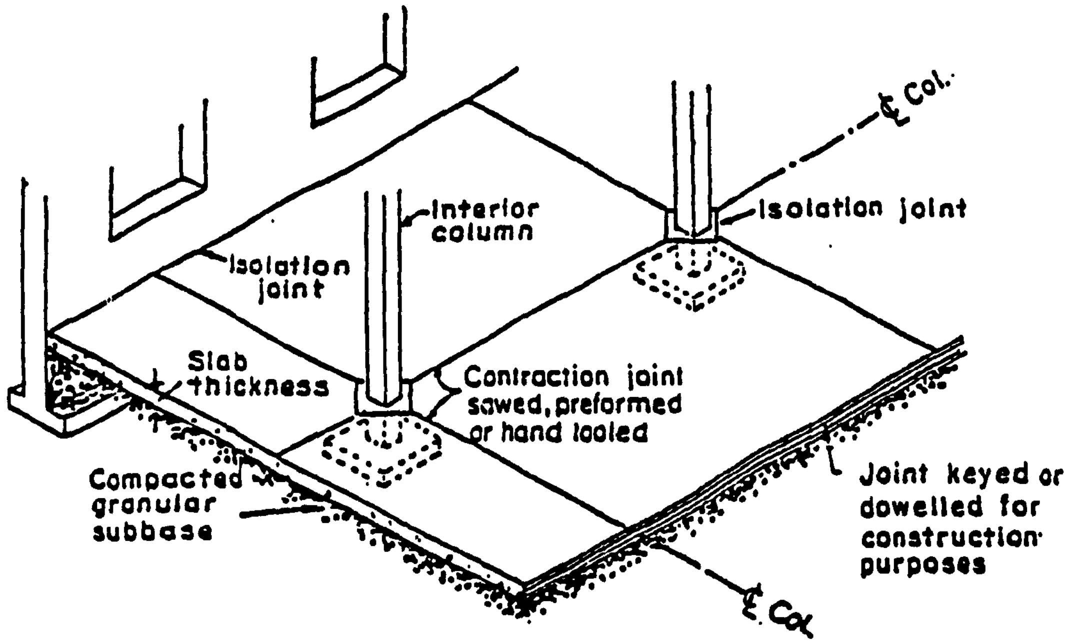



Figure 5.1: Typical Slab-on-grade

### 5.1.1 Basic Design Considerations

The concrete slab on grade is designed to transmit all stresses resulting from imposed loads directly onto the subgrade. In addition, the slab must be designed to withstand the stresses resulting from volumetric changes in the concrete. The designer must also provide a concrete mix which is of sufficient workability for placement, but of such consistency that it does not segregate or bleed excessively. The essential performance requirements of a slab on grade can be summarized by the following four criteria:

1. Adequate load bearing capacity:

The factors which have the greatest effect on load-bearing capacity are: the modulus of subgrade reaction (k), the slab's thickness, and the concrete's compressive strength. The modulus of subgrade reaction accounts for the soil's properties and depends on the type of soil, its moisture content and degree of compaction. The better the compaction, the higher the modulus k and the smaller the bending moment in the slab because it cannot sink into the subgrade as easily. Load bearing capacity is also a function of slab thickness and of the concrete's compressive strength.

2. Minimal cracking and curling:

Cracking is caused by the drying shrinkage that occurs when the water in the concrete mix which is in excess of the amount needed to hydrate the cement, but which is necessary to provide the workability needed for placement, evaporates from the upper surface of the slab. Differential shrinkage between the top and bottom of the slab causes upward curling of slab edges and slight depression of slab centers. Shrinkage cracking and curling are the most common problems affecting slabs on grade, and, although greatly influenced by site conditions, they can be effectively controlled by specifying low shrinkage mixes and by providing isolation and contraction joints and non-structural steel reinforcement ("Guide" 1989; Ytterberg 1987).

3. Abrasion resistant surface:

Surface abrasion resistance is directly related to the construction techniques used. It is mostly a function of the quality and amount of troweling and of the application of mineral hardeners to the floor surface. More specifically, abrasion resistance is a function of the water-cement ratio at the surface of the floor and of the quantity and quality of aggregate (Ytterberg 1987).

4. Flat and level surface:

Surface flatness and levelness are exclusively determined by the quality of the workmanship and are discussed in the following section.

### 5.1.2 Traditional Construction Practices

Figure 5.2 shows the typical tasks involved in slab on grade construction. Concrete can be delivered to the workface by wheel barrow, buggy, pump, conveyor, or can be discharged directly from the truck. It is then spread in the area between side forms and is screeded to their elevation. Screeding, the act of striking off the concrete in order to bring it to the proper grade, is accomplished using a straigthedge, a straight piece of wood or metal, approximately 1.8 to 3.7 m (6 to 12 ft) long. As the straightedge is pulled over the surface in a sawing motion, the low spots behind are filled by placing additional concrete

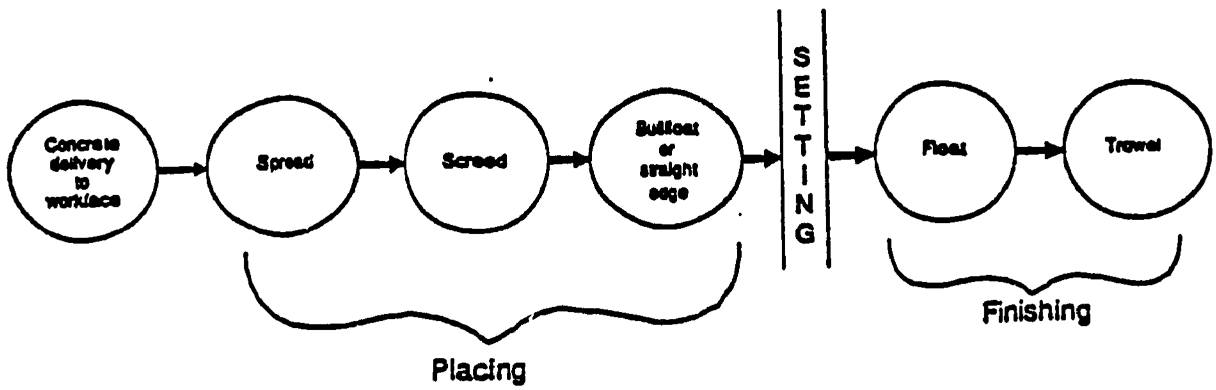



Figure 5.2: Slab-on-Grade Construction Operation Task Breakdown

with a shovel, and the surface is re-screeded. The concrete is straightedged to the required elevation, obtained through the use of either dry screed guides, i.e., grade stakes inside the area to be concreted (see Figure 5.3), or wet screed guides, i.e., elevation guides struck off in the fresh concrete at the time of pouring.

Immediately following screeding, bullfloating eliminates ridges and voids left in the surface by the straightedge, and slightly embeds coarse aggregate. A bullfloat typically consists of a 1.8 m (6 ft) lightweight aluminum handle at the end of which is a 200 mm (8 in) wide by 915 mm to 1.5 m (3 to 5 ft) long float blade. The bullfloat is moved back and forth, smoothing and consolidating the surface.

Finishing begins once the concrete has set but before the surface has hardened, and involves two tasks, floating and troweling. Both require sweeping a machine, consisting of four removable blades attached to a rotating shaft, over the concrete surface. Although several models are available, the most common are the 915 mm (36 in) and 1.2 m (46 in) diameter walk-behind models. Float blades are wider than trowel blades and are turned up at the edges to prevent from digging into the surface. During floating the blades are always kept flat, but are tilted during troweling to increase pressure on the surface. Power floating, always done perpendicular to the direction of bullfloating, embeds large aggregates, removes bumps and valleys, compacts the concrete, and consolidates the mortar at the surface in preparation for final finishing (Peterson 1986). Power troweling is done after floating to produce a dense, smooth and hard surface (Peterson 1986).

In instances where the floor will be subjected to considerably heavier and more frequent traffic, a dry pre-mixed powdered hardener, known as a 'dry shake', is incorporated in

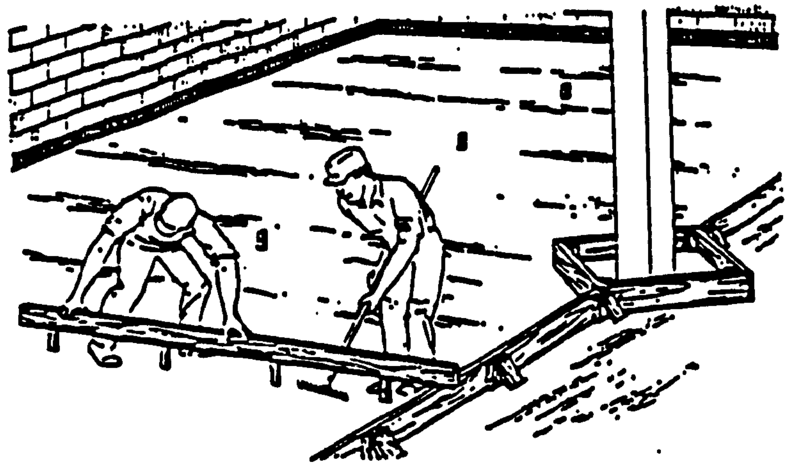


Figure 5.3: Setting Fixed (Dry) Screed Guides ("Guide" 1989)

the top 1/8 inch of the slab. Approximately 2/3 of the amount specified for the area is evenly distributed on the surface after the first floating; upon darkening slightly from moisture absorption, the surface is re-floated and the rest of the shake can be applied, thereafter floating and troweling the surface as usual. Once hardened, the concrete surface is cured and contraction joints are saw-cut and filled with epoxy resins or elastomeric sealants.

### 5.1.3 Quality: Definition and Major Contributing Factors

For the purpose of this work, the quality of a slab on grade is determined by its conformance with the four essential performance requirements described in Section 5.1.1. Whereas standard test procedures exist to evaluate the requirements related to the properties of the concrete mix, such as strength, slump, and shrinkage, there have been until recently few effective methods for specifying the essential performance requirements of concrete slabs: such is the case for thickness tolerances used to specify slab load bearing capacity (Gustafero 1989; Snell and Rutledge 1989), and abrasion resistance tolerances ("Guide" 1989).

With respect to flatness and levelness, the traditional specification method, known as the "3.2 mm in 3.05 m" rule (1/8 inch in 10 ft), requires measuring the maximum gap under a a 3.05 m (10 ft) long straightedge. Widely recognized as a poor method for specifying floor tolerances (Phelan 1988; Stephan 1989), it is being replaced by a new specification, called the F-number method, in which the floor surface profile is determined by sampling, within 24 hours after placement, a number of normally distributed floor elevations ("Standard" 1988). Numerical values are then assigned to describe flatness, $F_f$, which is characterized by the maximum floor curvature over 610 mm (24 in), and levelness, $F_l$, which is characterized by the floor slope over a distance of 3.05 m (10 ft). $F_f/F_l$ classifications for different floor categories are given in Table 5.1.

Slab on grade construction should follow the basic functional steps of any concreting operation, and should therefore adhere to standard practices for concrete handling, placing, finishing and curing, as defined by the American Concrete Institute (ACI) ("Guide" 1989). There are however a number of unique factors to be considered in achieving a quality slab. Summarized in Table 5.2, these include:

1. Subgrade preparation:

Achieving the design thickness throughout the slab, an important factor in meeting its load bearing capacity, is a function of both subgrade and surface profiles, and is therefore dependent on the precision of both grading and concrete placing operations. Subgrade preparation could be enhanced by semi-automated compaction control systems and laser-guided grading systems currently available on the market (A1,A2), whereas surface profiles can be improved, as will be seen, by laser-guided screeding machines.

2. Placement Width:

The placement width must be carefully considered, as the wider the dimensions of the pour, the harder it is to achieve a flat and level, crack-free surface. The distance between forms also affects the finishers ability to work, and the amount of shrinkage cracking and curling. Although jointing at closer intervals reduces total slab movement, forming requirements are increased and production rates are reduced. Experience has shown that

| Classification | $F_f$ | $F_l$ | Approximate gap under 3.05 m (10 ft) straightedge |
|---|---|---|---|
| minimum acceptable | 13 | 10 | - |
| conventional: bullfloat<br>straightedge | 15<br>20 | 13<br>15 | 12.7mm (1/2 in.)<br>7.9mm (5/16 in.) |
| flat | 30 | 20 | 4.8mm (3/16 in.) |
| very flat | 50 | 30 | 3.2mm (1/8 in.) |
| superflat | 100 | - | - |

Table 5.1: Slab-on-grade Surface Tolerance Classifications
("Guide" 1989)

| | Essential Performance Requirements | | | |
|---|---|---|---|---|
| | Load Bearing Capacity | Abrasion Resistance | Levelness | Flatness |
| Factor/ operation | subgrade compaction | timing of finishing operations | setting side forms | bullfloating & troweling |
| | subgrade & surface profiles | amount of troweling | placement width | spreading hardeners |
| | | | wet screed guide | re-straightedging operations |

Table 5.2: Summary of Factors and Operations Having an Impact
on Slab-on-Grade Quality

it is very difficult to build a floor with a flatness/levelness greater than $F_f30/F_l20$ when forms are more than 6.1 to 7.6 m (20 to 25 ft) apart, and superflat floors, $F_f100$ or higher, if forms are more than 4.3 to 5.5 m (14 to 18 ft) apart ("Guide" 1989; Phelan 1988).

3. Screeding:

Of all the floor-placing and finishing operations, the contractor's accuracy in setting side forms at the proper elevation around the area to be concreted and his ability to screed the concrete to that elevation have the greatest effect on floor levelness: in particular, the use of wet screed guides instead of dry screed guides limits achievable floor flatness/levelness to $F_f20/F_l20$ ("Guide" 1989). The ACI recommends using fixed (dry) screed guides whose elevation has been previously established.

4. Bullfloating:

Each step performed after screeding tends to make the floor less flat, because bullfloats and power trowels are by nature wave inducing devices: bullfloating in particular, makes the achievement of flatness greater than $F_f20$ extremely difficult ("Guide" 1989). A 50% increase in $F_f$ can be obtained by the simple substitution of a straightedge in place of the bullfloat. The ACI states that straightedges are the only tools capable of flattening the plastic concrete, since they alone provide a reference line against which the resulting floor profile may be compared ("Guide" 1989). The key to surface flatness is therefore the timing and number of re-straightedging operations: the more this operation can be undertaken, at the proper time, the flatter the floor can be made. In fact, producing superflat floors is almost exclusively determined by corrective straightedging operations performed after each power floating and troweling pass (Phelan 1988).

5. Timing:

Any operation performed while there is excess moisture or bleeding water on the surface will reduce compressive strength (durability) at the surface and cause dusting or scaling ("Guide" 1989). Therefore, both screeding and bullfloating must be completed before any excess moisture or bleeding water is present on the surface, and finishing operations can only start after all water has evaporated or been removed from the surface.

Climactic factors are an important influence on all concreting operation, affecting both concrete properties and the abilities of the workers. Temperature and humidity affect shrinkage cracking and edge curling, and also the time during which the concrete is plastic enough to permit straightening. If the concrete sets to fast because of hot temperatures, finishers may have problems achieving desired flatness; if it sets too slow because of cold temperatures, finishing work is considerably slowed. In general the ACI recommends that no operation after bull floating should be done until the concrete will sustain about a 1/4 inch footprint indentation ("Guide" 1989).

6. Finishing:

Several float and trowel passes will be required depending on the specified surface quality. Additional troweling increases the compaction of fines at the surface, giving greater density and more wear resistance. More passes, however, will not improve surface flatness. Therefore, if both high wear resistance and flatness are required, re-straightedging operations must be performed between each successive pass.

7. Hardeners:

Application of shake on hardeners has a significant effect on floor flatness. Based on

North-American experience, facilities with hardened surfaces typically exhibit flatness values between $F_f25$ and $F_f40$, with corrective straightedgings; $F_f45$ appears to be the maximum flatness that a knowledgeable floor contractor would agree to deliver on a floor that has a hardened surface (Phelan 1988).

8. Curing:

The provision of moisture by curing is an extremely important step, and should be done promptly, especially in dry weather, as it is essential in developing sufficient strength to produce a hard and durable surface.

## 5.2 Operational Analysis

Based on the results of the structured interviews and site surveys, an in-depth analysis of manual placing and finishing, semi-automated placing, and robotic finishing tasks is first performed. Quality controlling elements of current practices are defined and compared with those of the automated tasks, as are productivity and production rates, and general receptivity to automation is investigated.

Since a clear understanding of the terms 'productivity' and 'production rate' will be required, a definition of both terms is given. In general, productivity measures the efficiency with which resources (inputs) are used in producing goods (outputs). Production rate simply measures the rate at which the units of output are produced.

Since concrete placing operations require large crews whose individual members work interdependently, productivity is expressed in terms of labour hours per unit of output, i.e., man-hours per cubic meter of concrete (m-hr/$m^3$). Thus, productivity is clearly different than production rate, which is expressed as units of output produced per unit of time, $m^3$/hr. Concrete finishing operations are also performed by crews, but since the individual members of these crews work independently of each other, productivity can be expressed as $m^2$/hr, making it synonymous with production rate.

### 5.2.1 Task Analysis

1. Conventional Manual Construction:

The results of the structured interviews and site investigations indicate very consistent work practices and methods among the contractors surveyed, and have recently been published (Moselhi et al. 1992). It was found that ready-mixed concrete is almost always used in the construction of slabs on grade, as none of the contractors indicated any experience with on-site batch plants. The most frequent (also the quickest and least expensive) way to pour a slab on grade is to deliver the concrete to the site by ready-mix truck, and to pour it directly on to the subgrade from the truck's chute. If truck access is restricted, the concrete is pumped, ferried by wheelbarrow or motorized buggy, or transported by conveyor, depending on job constraints.

Although dependent on individual schedule and resource constraints, when pouring directly from the truck, the average daily pour size on large jobs was found to vary between 1859 to 2788 $m^2$ (20,000 to 30,000 $ft^2$) for 125 to 130 mm (5 to 6 in) thick floors.

When no special requirements are specified, floors are usually poured in strips approximately 18.3 to 30.5 m (60 to 100 ft) wide, located to coincide with the bays of the structure under construction[8]. Although most of the contractors had experience with narrow-strip construction, i.e., pour widths of less than 7.6 m (25 ft), it was found that this was not a commonly specified construction method. Only one contractor had any experience with superflat floor construction.

Most contractors use a rotating laser level with wet screed guides to place the concrete at the proper elevation, although some still use optical transits: none has indicated any experience using dry screed guides. Figure 5.4 shows both the rotating laser and the operator setting a wet screed guide. The operator first strikes off a patch of concrete with a hand trowel to what he perceives as the proper elevation; after checking the elevation of the concrete patch against the level of the rotating laser beam with the elevation rod, the operator either removes some concrete if he is above level, or adds concrete if he is below level, checking the elevation until it is right. Using a straightedge, the screeder then uses the wet screed guides as a reference when striking off the rest of the surface (see Figure 5.5).

It was found that all contractors regularly use the bullfoat after screeding (see Figure 5.6). Re-straightedging operations were found to be performed only when explicitly specified, and only two contractors were found to have had any experience with this task.

The beginning of finishing operations depends on ambient conditions (temperature, humidity, wind), and should take place neither too early nor too late in the concrete

8 This pour width typically represents 2 to 3 bays.

Figure 5.4: Setting a Wet Screed Guide

Figure 5.5: Screeding with a Straightedge

Figure 5.6: Bullfloating

setting process. The timing of finishing operations requires considerable judgement, particularly in cold (slow setting) conditions, when finishing should take place as late as possible, and in hot (rapid setting) conditions, when finishing should start as early as possible. Under the ideal environmental conditions assumed for this study, contractors indicated and average setting time of 4 hours before beginning finishing operations: setting times observed in the field varied from 3/4 hour during a very hot summer day (32°C) to 7 hours on a cold winter day (-12°C).

Finishing operations typically involve a minimum of three float and three trowel passes, although more troweling is sometimes performed. The beginning of each successive pass is staggered to allow the concrete to harden further. Although also dependent on ambient conditions, a one hour interval between successive passes represents an appropriate duration for the conditions assumed in this study.

It was found that all contractors use the mechanical power trowel (see Figure 5.7) and resort to manual finishing of inaccessible areas. The curing compound is usually applied to the surface immediately after it has received the final finishing: moisture retention by spray-applied compound is the most widely used curing method.

Based on the information collected in this survey, the conventional manual construction operation is defined to be composed of direct from truck discharge, wide pour widths, usually 2 or 3 bays wide (18.3 to 30.5 m; 60 to 100 ft), wet screed guides, bullfloating, finishing consisting of 3 float and 3 trowel passes, and curing by spray-applied compound.

Figure 5.7: Manual Finishing with Mechanical Power Trowel

In order to establish a basis for productivity and economic analyses, a "unit slab" representing a size into which a larger slab could be conveniently subdivided, can be conservatively defined as: a 30 m X 62 m (100 ft X 200 ft), 150 mm (6 in) thick slab, made of 24 Mpa, 125 mm (5 in) slump concrete, and possessing nominal reinforcement. Many contractors have indicated that, in the absence of mitigating constraints, the unit slab as defined would be their preferred daily pour size because it represents a full day's work without overtime for the placing crew and enables better quality control.

2. Semi-Automated Placing:

As shown in Figure 5.8, the semi-automated concrete placing cycle can be defined as follows. The operator positions the machine with approximately a one foot overlap with the previous pass. Concrete is poured directly from the truck onto the subgrade in the 3.7 m x 6 m (12 ft x 20 ft) section covered by the machine. It is spread by workers using shovels and rakes to approximately 25 mm (1 in) above the finished floor grade. The operator extends the boom, which is then automatically retracted, maintaining the proper carriage elevation. Although too much or too little concrete in front of the carriage can cause bumps or valleys that have to be corrected with another screeding pass, the situation where a cycle must be repeated because of unsatisfactory screeding was found to occur very infrequently. The operator then drives the machine approximately 3.7 m (12 ft) across the pour width to the next section being poured and repeats the process.

When working on the perimeter of the slab, the carriage is stopped approximately 1 m (3.28 ft) before the edge of the slab, which must then be poured and screeded by hand.

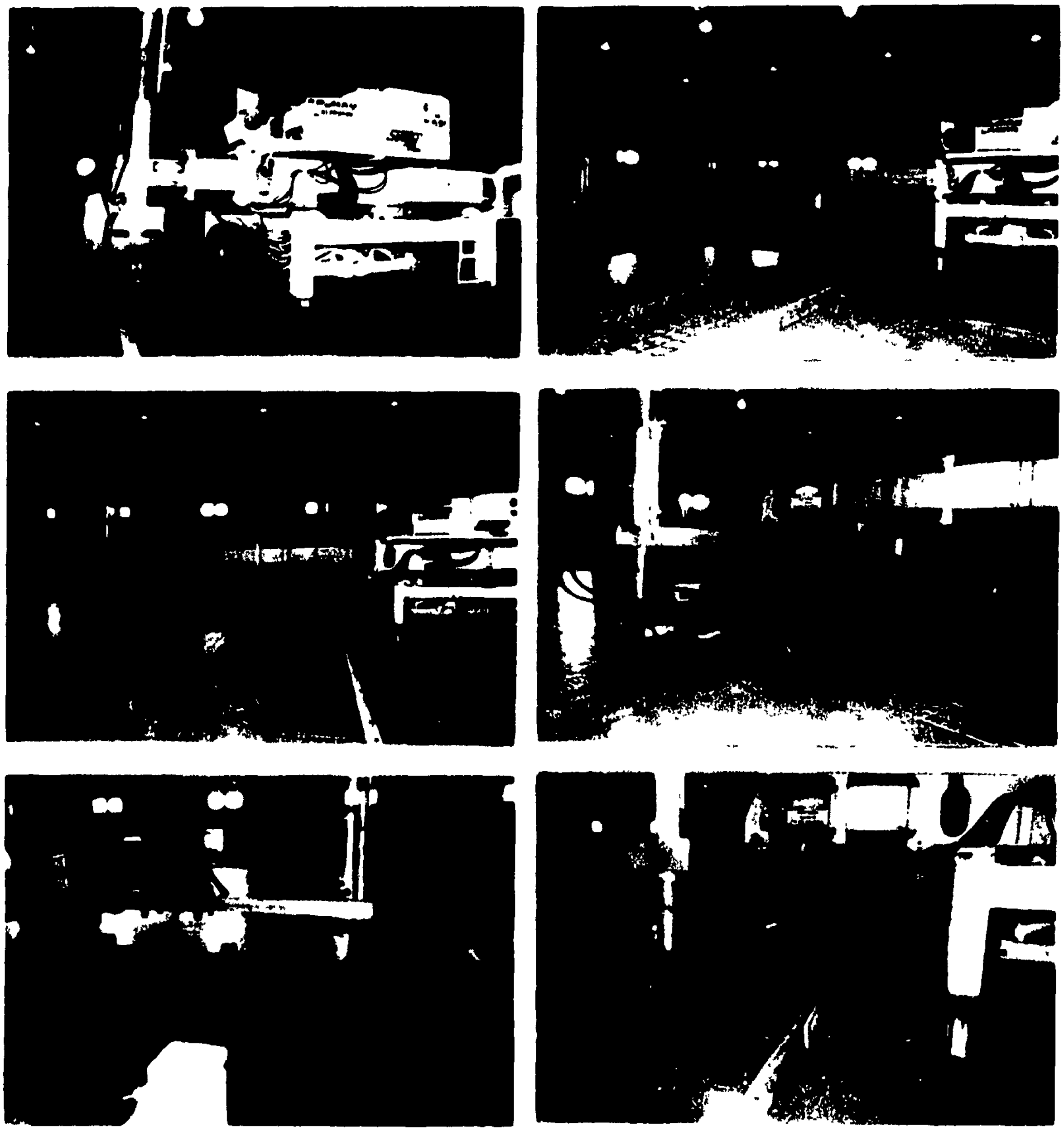


**Figure 5.8: Semi-Automated Concrete Placing Cycle**

The sequence of daily pours is therefore planned to minimize the number of perimeter edges: most can be planned with one or two perimeter edges which must be manually screeded. Also to be screeded manually are areas adjacent to columns.

Other than the elimination of most screeding operations, it was found that semi-automated placing does not significantly change the way which contractors usually plan and carry out their work. When discharged from the truck, for instance, the concrete must still be manually spread before the laser-guided screeder. The type of concrete, average daily pour sizes, pour widths, and finishing operations remain generally un-modified. As will be discussed later, this minimal disruption of the contractor's usual way of working was found to be a major factor in the acceptance of this technology.

3. Robotic Finishing:

After viewing videotapes of the various finishing robots, contractors had one main concern regarding its use. In order to maintain control over the quality of his work, the finisher must generally exercise considerable judgement, as it is crucial to physically feel and see the effects of the trowel on the concrete surface in order to judge where and how fast to travel.

The first float pass in particular is probably the most critical step because, at this point, the surface is still plastic enough to allow minor defects to be corrected. These defects, for example, may require the operator to use a different finishing pattern: low spots, for instance, are filled by going around them in a clockwise direction, then continuing with the regular pattern. Also during the first pass, the operator recognizes the areas that set faster and must float them first: these typically include areas adjacent to walls, columns, doorways, or specific areas that may be exposed to the sun or wind. (note in Figure 5.7, for example, that the area adjacent to the wall has been floated first: also note the difference in surface texture between the area having received the first pass and the area yet un-treated).

Consequently, none of the contractors interviewed were confident about removing the operator from the concrete surface during floating operations; all, however, indicated that they would not hesitate using the robot during troweling operations. They did not anticipate extra requirements due to areas which must be finished by hand since these areas would have to be done manually even if mechanical equipment were used.

### 5.2.2 Quality Analysis

While recognizing that achievable surface quality can vary considerably for a given construction method, the information collected in this survey suggests that the steps taken by Montreal area contractors in the construction of a conventional concrete slab on grade limits the achievable surface quality to approximately $F_f20/F_l20$. The principal factors that limit quality are, the use of wide pour widths, the use of the bullfloat, and the difficulty in achieving correct elevations with wet screed guides.

Eliminating the need for wet screed guides which limit achievable levelness to $F_l20$, is one of the greatest benefits of semi-automated placing. Analyses of floors produced by the laser-guided screeding machine indicate a capacity to achieve a surface levelness of approximately $F_l45$, with placement widths of 30 m (100 ft) or more ("Laser-Guided"

1989; Fricks 1991). Such a floor, if done conventionally, would require pouring the concrete in 6 m (20 ft) strips and several corrective straightedgings. Another significant improvement is achieved by eliminating the use of the bullfloat, which limits achievable flatness to $F_f20$, through the use of the straightedge. Flatness in excess of $F_f40$ have been measured with the laser guided screeder ("Laser-Guided" 1989).

The machine's ability to handle stiff concrete, with slumps as low as 75 mm (3 in), leads to less bleeding and generally higher quality floors. Less bleeding and lower slump also speed the setting process thereby reducing the operation's duration. When used in conjunction with semi-automated subgrade compaction control systems and laser-guided grading systems currently available on the market, semi-automated placing can lead to improved strength through more uniform slab thickness and, in addition, may also allow material savings.

With respect to the surface quality that can be achieved with robotic finishers, as was previously stated, significant increases in flatness do not result from better or more finishing, but rather from corrective re-straightedging operations performed between successive floating and troweling passes. However. extensive testing of the robots in Japan has indicated a finishing quality (surface flatness) which is at least equal to that obtained by a human operator with a machine (Arai et al. 1988; Kikuchi et al. 1988).

### 5.2.3 Productivity Analysis

1. Concrete Placing:

Based on survey information about crew sizes and work durations, the productivity of manual and semi-automated concrete placing is estimated. Figure 5.9 presents a comparison of concrete placing productivity, defined as the number of man-hours required to place one cubic meter of concrete for a 150 mm (6 in) thick slab, for both conventional manual and semi-automated placing. The best-fit functions for the data are;

$$\log(P_r) = \log 1.66 - 0.18\log(A), \tag{5.1}$$

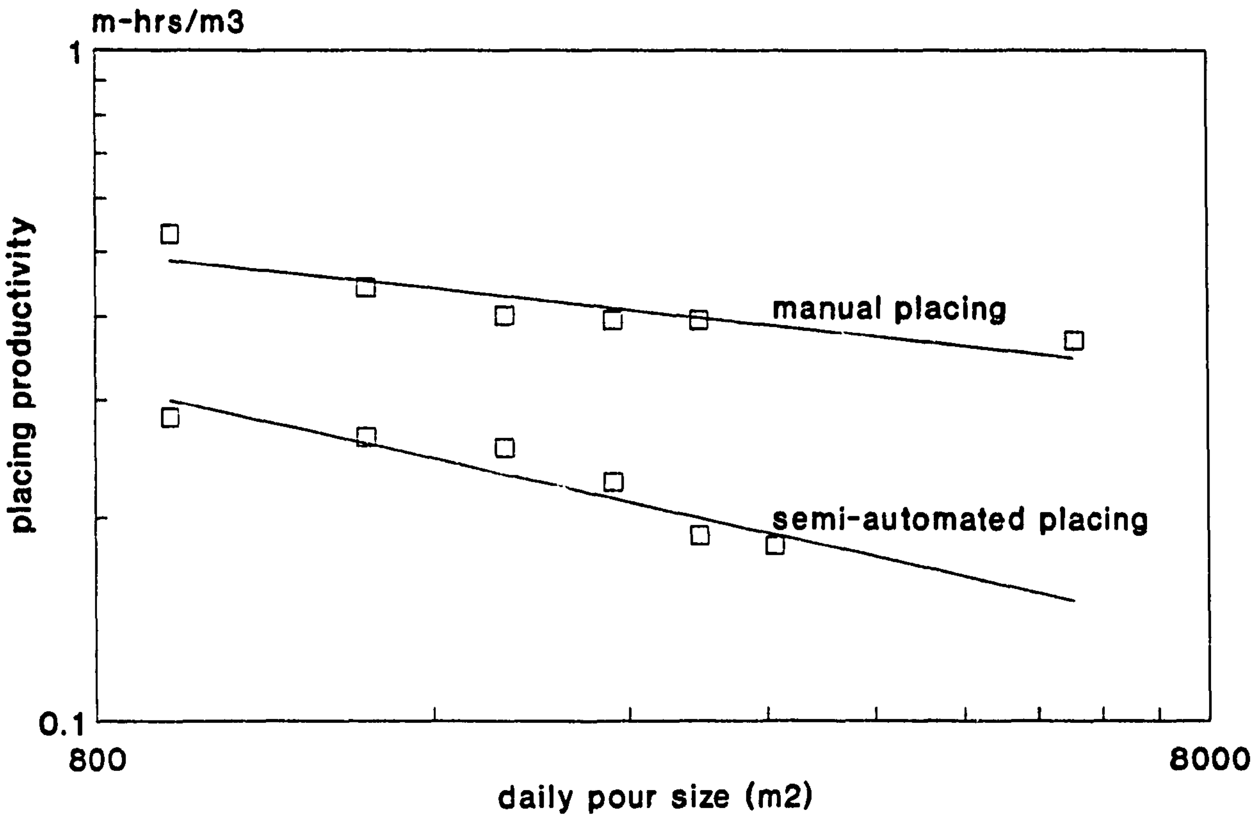
with a coefficient of correlation of $r^2$=0.78, for manual placing, and,

$$\log(P_r) = \log 3.7 - 0.36\log(A), \tag{5.2}$$

with a coefficient of correlation of $r^2$=0.88, for semi-automated placing,

where: $P_r$ = placing crew productivity (m-hrs/m$^3$)
A = daily pour size (m$^2$)

In general, concrete placing productivity was found to vary with the size of the daily pour: for small pours ($\approx$ 930 m$^2$; 10,000 ft$^2$) the productivity is lower since relatively large crews must be assembled; as the daily pour size increases, so does productivity benefiting from the optimum utilization of the crew and the learning curve effect.




•N.B. expressed in m-hrs/m3, the higher the value the lower the productivity

Figure 5.9: Relationship Between Placing Productivity and Daily Pour Size for Manual and Semi-Automated Placing

2. Floor Finishing:

The production rate of concrete finishing varies greatly depending on the experience of the operator, the amount of water in the concrete, and the weather. If the concrete is free of excess water, and the weather is very warm, it was found that finishing may start as soon as half an hour after the concrete is placed and screeded; in this case, the rapid hardening will cause many difficulties to the contractor who must work fast. If the concrete contains excess water, and the weather is cold and damp, finishing may start as much as six hours after placing and screeding, and the whole floor may take more than 50% longer to finish.

Accordingly, contractors' estimates of finishers' production rate varied enormously, ranging from 93 to 370 $m^2$/hr (1,000 to 4,000 $ft^2$/hr). Site measurements of a 1.2 m (46 in) power trowel, under near ideal ambient conditions, indicate a production rate in the range of 185 to 250 $m^2$/hr (2,000 to 2,700 $ft^2$/hr). This is slightly lower than reported finishing production rates, i.e., 280 to 370 $m^2$/hr (3,000 to 4,000 $ft^2$/hr) with a 1.2 m (46 in) machine (Peurifoy and Oberlender 1989). Comparatively, the reported production rate of floor finishing robots (Table 4.1) varies from 300 to 800 $m^2$/hr (3,228 to 8,608 $ft^2$/hr).

3. Placing and Finishing:

The successful construction of a concrete slab on grade depends on achieving the target production rate during every step of the operation: thus the concrete delivery rate, the placing crew's production rate and the finishing crew's production rate must be equivalent. If, for example, the finishing crew's production rate was less than the placing crew's, the concrete would harden before it could be finished in time, and if the finishing crew's production rate was greater, the crew would have to wait for the concrete to set.

Therefore any equipment that can increase the production rate of either delivery, placing, or finishing cannot be used to its full potential unless a similar production rate increase is obtained in the other operation.

The largest contractors, for example, indicated that the fastest rate at which they would pour a conventional slab on grade is approximately 45 to 50 $m^3$/hr (58.8 to 65 cu yd/hr). Local ready-mix batch plants indicated production capacities of 100 to 150 $m^3$/hr (130 to 196 cu yd/hr) and a capacity to supply concrete at up to 75 $m^3$/hr (98 cu yd/hr) without special planning[9], suggesting that the delivery of concrete is not limiting contractors' production rates. The limitation was found to be solely due to the fact that greater production rates require manpower in excess of that which is available to most firms. In particular, overcoming shortages of concrete finishers was found to be the main problem with increasing production rates, and, as will be discussed in the next section, was found to be the prime motivator for automation by local contractors.

Subject to such manpower constraints, the greatest production rate for which semi-automated placing is performed was found to be approximately the same as that which can be achieved by manual placing. Thus, although a number of British contractors have reported achieving production rates varying between 72 and 100 $m^3$/hr (105 to 131 cu yd/hr) with the laser-guided screeding machine (Barfoot 1988; "Fast Track" 1989), its use by the local contractor is limited to a production rate equivalent to that of the manual placing operation by the inability to add manpower, particularly in finishing, rather than by the inability to achieve the concrete supply rate. Robotic finishers could

9 From the author's telephone survey of 5 Montreal area concrete batch plants.

help contractors benefit from the full potential of semi-automated placing. For example, assuming a 150 mm slab, the upper bound of robot production rates listed in Table 4.1 is beyond the range of semi-automated placement rates.

### 5.2.4 Receptivity to Automation

All of the contractors had heard of semi-automated placing equipment but none had heard of robotic finisher. The contractors were extremely interested in the idea of an automated finisher, but had very specific technical questions that had to be resolved before being confident in the technology. In considering the automation of either placing or finishing, the contractors' prime motivating factors were found to be:

1. easing labour shortages
2. reducing labour costs
3. improving quality

Although these factors are also important motivators in manufacturing operations (Ayres and Miller 1983; Hamidi-Noori and Templer 1983), the different priorities reflect the different nature of the business and working environments. For example, easing labour shortages seems to be more important for concrete contractors than for manufacturers. During the interviews, each contractor drew particular attention to the difficulty in finding qualified finishers and to the cost of training new ones[10].

**10** Many contractors consider that it takes 2 to 3 years for an inexperienced worker to obtain the necessary skills to be considered a qualified floor finisher. This training can represent a considerable investment, particularly given the small size of many concrete contractors.

When discussing their acceptance of automation, the following factors were considered to be the most important barriers:

1. costs
2. disruption of traditional working methods
3. complexity of equipment and reliability.

It is not surprising that cost is the most important barrier to automation for concrete contractors, just as it is for manufacturers. It can be expected to be an even more serious barrier in construction since the cost of automation represents a larger proportion of operating revenues in construction than in manufacturing.

Typically, employee and union acceptance are also very important issues in manufacturing. This was not found to be a problem for concrete contractors possibly because automation is seen as complementing not competing with human workers. Rather, the degree to which automation disrupts traditional work methods was found to be a more important barrier to its acceptance. Since automated placing or finishing neither eliminates nor substantially modifies any of the craft's traditional work tasks, they are favorably perceived.

Since contractors have no experience with automation, an important barrier was found to be the perceived complexity and reliability of the equipment. Automated equipment must be easy to operate. It must be push button simple; for example, contractors were horrified to learn that some programming may be required with the robotic finisher. The equipment must also be proven to be reliable for all types of concrete and weather conditions. It must be designed so that it can be manhandled like all other construction equipment. Adequate support and service must also be available if breakdowns occur.

### 5.3 Simulation

A number of mathematical and analytical tools are available for modeling construction operations: MicroCYCLONE is a microcomputer based simulation program using the CYCLONE (CYCLic Operations Network) methodology developed by Halpin and Woodhead (1976), and is one of the first modeling methodologies specifically developed for construction operations; INSIGHT (Interactive SImulation of Construction Operations using Graphical Techniques) developed by Paulson (1987), also based on CYCLONE methodology, operates on microcomputer and requires a link with a videocassette recorder; and SLAM II, a general purpose simulation language developed by Pritsker and Alan (1986) which can be used in a number of industrial processes and construction operations. MicroCYCLONE is generally accepted as a powerful tool to model and simulate construction operation and was chosen for this analysis mainly because of its simplicity and versatility.

The CYCLONE modeling methodology provides two basic modeling shapes, squares and circles, to describe, respectively, active and passive work states: together with directed arrows (arcs) for resource flow direction, they help provide a quick visual grasp of the structure of a construction operation. In total, 4 basic modeling elements are provided (see Figure 5.10). For a detailed definition of the language, the reader is referred to the MicroCYCLONE system manual (Halpin 1989a) and user's manual (Halpin 1989b).

### 5.3.1 Simulation Parameters and Assumptions

Simulations are performed for the placing and finishing of a unit slab, for each of the four levels of automation described in Section 4.2.2. The following assumptions are made:

1. Concrete placing productivity for manual and semi-automated placing is obtained, respectively, from Equations 5.1 and 5.2, and amounts to 0.42 and 0.25 m-hrs/$m^3$. In the case of the fully automated operation, where increased production rates can be sustained throughout the operation, a conservative production rate of 72 $m^3$/hr is assumed, representing the lower bound of reported production rates for the semi-automated screeder. Since ideal ambient conditions are assumed for the entire duration of the operation, finishing rates are assumed to be equivalent to that of placing for all cases.
2. Work task breakdowns and crew sizes for each level of automation are given in Table 5.3, and are based on the construction practices described in Section 5.2.1. It must be noted that the use of the robot finisher, in accordance with the contractors' comments, is limited to troweling: considered to require more judgement, floating operations are assumed to be performed by the human operator with the mechanical power trowel.

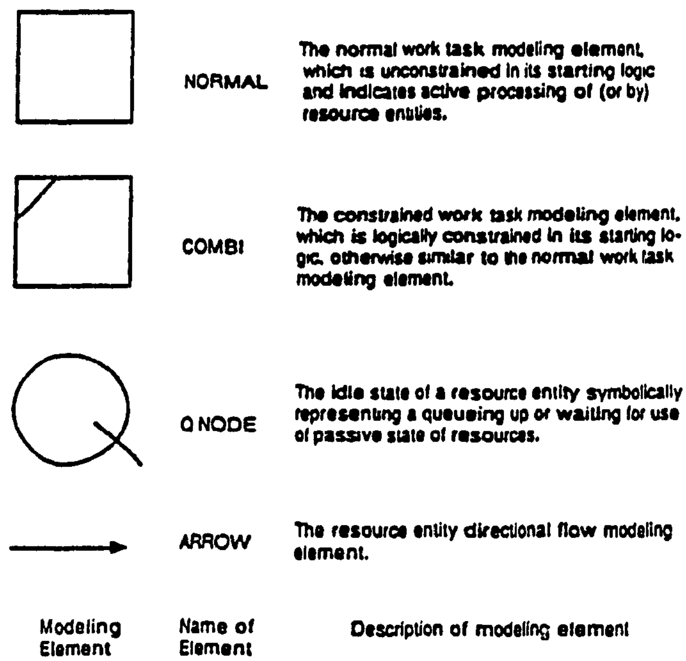



Figure 5.10: MicroCYCLONE Basic Modeling Elements (Halpin and Woodhead 1976)

| Work Task | Crew Size | | | |
|---|---|---|---|---|
| | MP/MF | SAP/MF | MP/RF | SAP/RF |
| Position Truck[1] | - | - | - | - |
| discharge concrete | 1 | 1 | 1 | 2 |
| spread concrete with shovel | 3 | 3 | 3 | 10 |
| lift wire mesh | 1 | 1 | 1 | 2 |
| Spread Concrete (Total) | 5 | 5 | 5 | 14 |
| place concrete wih rake | 3 | - | 3 | - |
| set wet screed guide | 1 | - | 1 | - |
| screed and bullfloat | 3 | - | 3 | - |
| drive laser screed | - | 1 | - | 1 |
| screed slab edges | - | 2 | - | 3 |
| Screed Concrete (total) | 7 | 3 | 7 | 4 |
| Wait Concrete set | - | - | - | - |
| 1st Float | 1 | 1 | 1 | 2 |
| Wait | - | - | - | - |
| 2nd Float | 1 | 1 | 1 | 2 |
| Wait | - | - | - | - |
| 3rd Float | 1 | 1 | 1 | 2 |
| Wait | - | - | - | - |
| 1st Trowel | 1 | 1 | | |
| Wait | - | - | | |
| 2nd Trowel | 1 | 1 | 1 | 1 |
| Wait | - | - | | |
| 3rd Trowel | 1 | 1 | | |

1 Activity not performed by concrete contractor's crew

Table 5.3: Work Task Breakdown and Crew Sizes for Various Levels of Automation

3. Work tasks have fixed durations. This is a reasonable assumption for this operation because although work tasks may be subject to small variations about a specific mean, the impact of these variations on productivity can be considered small or insignificant. Durations for the specified work tasks are presented in Table 5.4.

4. Sufficient concrete is available to ensure that the simulation is not constrained due to lack of concrete. This implies that the supply of concrete is constant during the entire length of the pour and is based on the production capacity of the crew. This assumption reflects actual working conditions encountered on site.

5. Concrete is discharged from each truck in 3 batches of 3.4 $m^3$ each (this volume represents the amount of concrete required for one cycle of the semi-automated placing machine). Thus a total of 83 cycles are required to pour the unit slab.

6. The relationships between concrete placing and the first floating pass, and between successive floating and troweling passes, are start-to-start with a lag to account for setting time as defined in Section 5.2.1. Thus, the start of the first floating pass is dependent on the start of concrete placing plus a four hour setting period. Similarly, the start of each finishing operation after the first pass is dependent on the start of the previous finishing operation plus a one hour setting period.

### 5.3.2 Operation Model

The model network diagram is presented in Figure 5.11 and can be broken down into three functional groups.

| Work Task | Duration (min) | | | |
|---|---|---|---|---|
| | MP/MF | SAP/MF | MP/RF | SAP/RF |
| Position Truck | 1 | 1 | 1 | 1 |
| Spread Concrete | 3 | 2.7 | 3 | 1 |
| Screed Concrete | 4 | 3.7 | 4 | 2 |
| Wait Concrete set | 240 | 240 | 240 | 240 |
| 1st Float | 7 | 6.4 | 7 | 3 |
| Wait | 60 | 60 | 60 | 60 |
| 2nd Float | 7 | 6.4 | 7 | 3 |
| Wait | 60 | 60 | 60 | 60 |
| 3rd Float | 7 | 6.4 | 7 | 3 |
| Wait | 60 | 60 | 60 | 60 |
| 1st Trowel | 7 | 6.4 | 7 | 3 |
| Wait | 60 | 60 | 60 | 60 |
| 2nd Trowel | 7 | 6.4 | 7 | 3 |
| Wait | 60 | 60 | 60 | 60 |
| 3rd Trowel | 7 | 6.4 | 7 | 3 |

Table 5.4: Work Task Durations for Various Levels of Automation

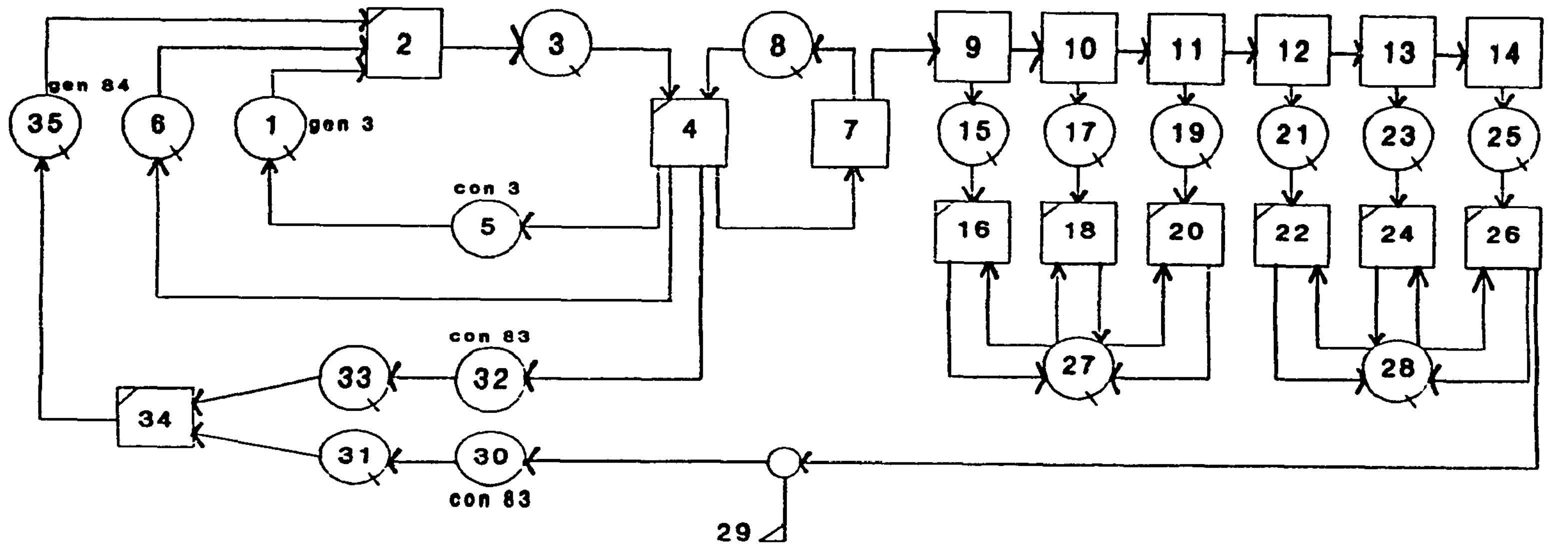



Figure 5.11: MicroCYCLONE Network for Slab-on-Grade Construction Operation

Nodes 1 to 8 represent the concrete placing cycle. At the beginning of this cycle, a concrete truck is generated at QUE node 1 and broken down into 3 batches of 3.4 $m^3$ each. The truck is positioned (COMBI node 2), and, if the concrete placing crew is available (QUE node 8), a batch of concrete is discharged (COMBI node 4). At this point commands are released which permit both the truck to be repositioned (QUE node 6) and the placing crew to spread, screed, and bullfloat the concrete (NORMAL node 7). When 3 batches are discharged, a command is given (FUNCTION node 5) to generate a new truck at QUE node 1.

Nodes 9 to 28 represent the concrete finishing cycle, composed of three floating passes (COMBI nodes 16, 18, 20) and three troweling passes (COMBI nodes 22, 24, 26). These are, in essence, sequential but staggered activities with the first pass starting 4 hours after the first batch of concrete is placed (NORMAL node 9) and the subsequent passes beginning at 1 hour intervals (NORMAL nodes 10, 11, 12, 13, 14).

Because of the 4 hour time lag between the placing and finishing cycles, and because MicroCYCLONE allows the use of only one counter per model, a mechanism is required to ensure that the proper number of flow units are both initialized and processed. Nodes 29 to 35 represent this mechanism, monitoring and controlling the total quantity of concrete in both placing and finishing cycles at all times.

### 5.3.3 Daily Production Cycles

Based on the data collected and the operational model just defined, a MicroCYCLONE program was developed (shown in Appendix B) and used to simulate each alternative based on the resources provided in Table 5.5. Simulation results for the placing and finishing of a unit slab are shown in Figure 5.12, in which the vertical axis represents the quantity of concrete being placed (in $m^2$ or $ft^2$), and the horizontal represents time (hrs).

Figure 5.12a shows the daily production cycle for conventional manual construction. The production rate of the placing crew is represented by the first line on the left. The six lines on the right of the placing line represents each of the three floating and three troweling passes. The total duration is 1129.5 minutes (18 hrs 50 min). Figure 5.12a also represents the daily production cycle for the automation of finishing alone because the production rate of the robot is limited by the achievable manual concrete placing rate.

The daily production cycle for the automation of placing alone is shown in Figure 5.12b, where the total duration is 1079 minutes (18 hrs), and in Figure 5.12c, for the automation of both placing and finishing. In this case, the total duration is 793.5 minutes (13 hrs 14 min).

The simulation clearly demonstrates that slab on grade construction is a sequential operation necessitating a constant production rate during delivery, placing, and finishing. There are no interacting cycles competing for resources: each batch of concrete which is discharged from the truck is processed by each work task without delay.

| Node | Resources | | | |
|---|---|---|---|---|
| | MP/MF | SAP/MF | MP/RF | SAP/RF |
| QUE 1 | 1 truck | 1 truck | 1 truck | 1 truck |
| QUE 6 | 1 permit to reposition truck | 1 permit to reposition truck | 1 permit to reposition truck | 1 permit to reposition truck |
| QUE 8 | 1 12-man placing crew | 1 8-man placing crew | 1 12-man placing crew | 1 18-man placing crew |
| QUE 27 | 3 concrete finishers | 3 concrete finishers | 3 concrete finishers | 6 concrete finishers |
| QUE 28 | 3 concrete finishers | 3 concrete finishers | 3 finishing robot +1 supervisor | 3 finishing robot +1 supervisor |
| QUE 35 | Counter initialized @ 1 | Counter initialized @ 1 | Counter initialized @ 1 | Counter initialized @ 1 |

Table 5.5: Resources Required for Simulation

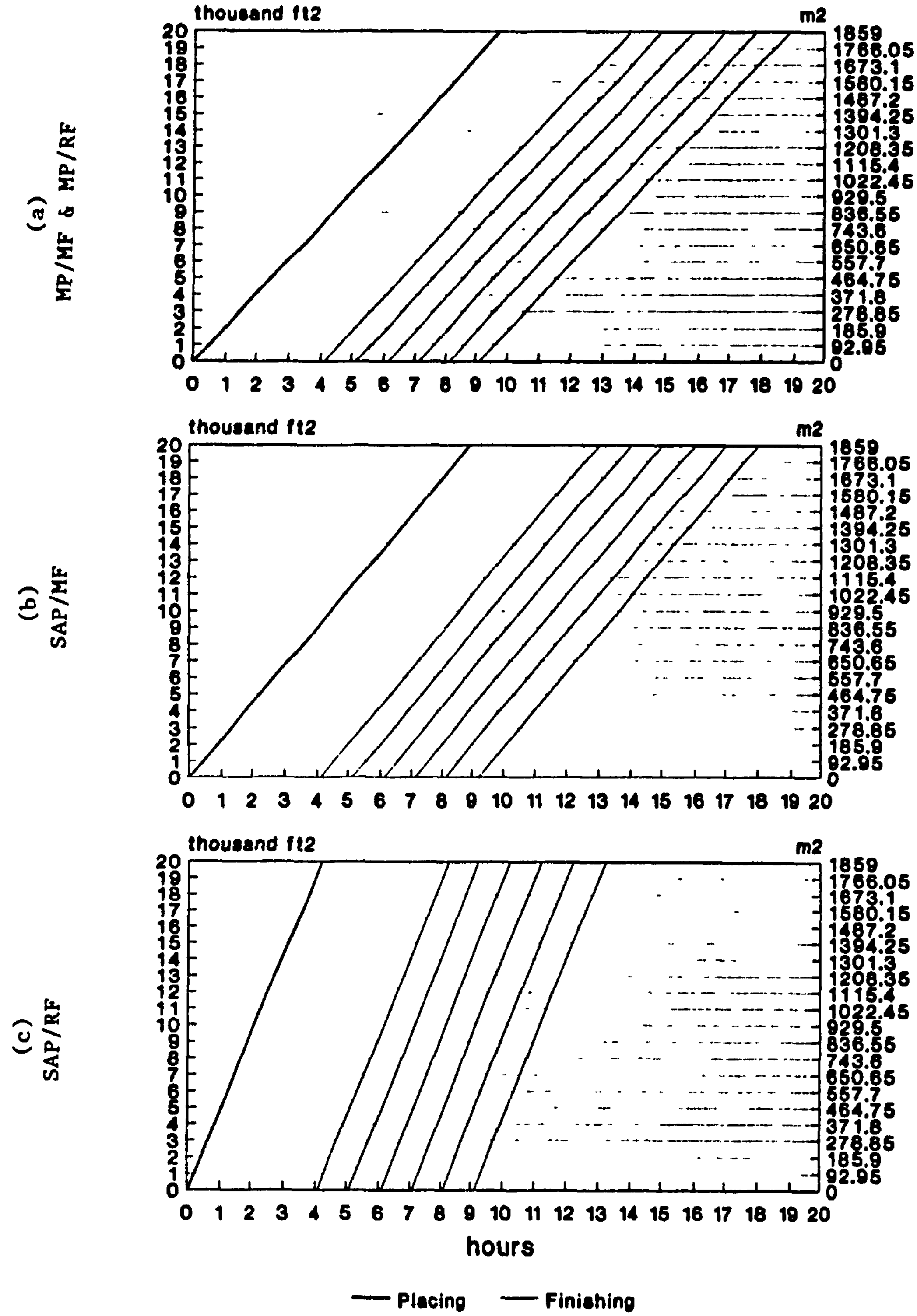



Figure 5.12: Production Cycles for Various Levels of Automation

The results of a change in the production rate of any operation by itself is immediately apparent, as the slope of that operation would either increase or decrease rendering it 'out of balance' with previous or successive operations. For example, if the arrival or repositioning time of a truck (nodes 1 to 5) exceeds the time required to place a batch of concrete (nodes 4-7-8), the placing crew's production rate would decrease, thus reducing the slope of the placing line. This would require a similar reduction in the production rate of the other operations until the delivery rate was brought back to normal.

## 5.4 Economic Analysis

Based on the simulations of the previous section, the economic feasibility of implementing the various levels of automation is determined by comparison with that of the conventional manual operation. The economic comparison is based on Net Present Value (NPV) analysis. The NPV is a classical financial technique used to compare investment alternatives (Davis and Pinches 1988). For the purpose of this study, it can be defined as the present value (PV) of all future, after-tax cash flows. Thus, for each alternative (Davis and Pinches 1988);

$$\text{NPV}=\sum_{t=0}^{n} R_t(1+i)^{-t}-\sum_{t=0}^{n} C_t(1+i)^{-t} \tag{5.3}$$

where: $R_t$ = after tax revenues at the end of period t, given by Eq. 5.4

$C_t$ = after tax costs at the end of period t, given by Eq. 5.5

i = minimum attractive rate of return (%)

n = economic life horizon

and,

$$R_t = BTR_t \cdot (1-T) \tag{5.4}$$

$$C_t = \begin{cases} CAPC & \text{for } t=0 \\ (LAB_t + MTNC_t + OPR_t) \cdot (1-T) - CCA_t \cdot (T) & \text{for } 1<t<n \\ (LAB_t + MTNC_t + OPR_t) \cdot (1-T) - CCA_t \cdot (T) - ECF & \text{for } t=n \end{cases} \tag{5.5}$$

where: $BTR_t$ = before tax operating revenues for period t

CAPC = capital cost of equipment

$LAB_t$ = cost of labour for period t

$MTNC_t$ = maintenance cost for period t

$OPR_t$ = equipment operation cost for period t

$CCA_t$ = capital cost allowance for period t

ECF = ending cash flow (in year n) such as salvage value and tax benefits or liabilities

T = tax rate

For Canadian income tax purposes, the method of depreciation used is the declining balance with one half of the net capital cost of the asset added to the asset pool in the first year, and the remainder added in the following year (Davis and Pinches 1988). Thus;

$$CCA_t = d \cdot UCC_t \tag{5.7}$$

and,

$$UCC_t = \begin{cases} \frac{1}{2} \cdot CAPC & \text{for } t=1 \\ C_0 \cdot \left(1 - \frac{d}{2}\right) \cdot (1-d)^{t-2} & \text{for } t>1 \end{cases} \quad (5.8)$$

where: $UCC_t$ = undepreciated capital cost for period t

d = depreciation rate (%)

The alternative with the highest NPV is the most economical. If, as will be shown to be the case, the revenues for each alternative are the same, then the objective of Equation 5.3 is to minimize Total Cost;

min (TC)

$$TC = \sum_{t=0}^{n} C_t (1+i)^{-t} \quad (5.8)$$

or Unit Cost,

min (UC)

$$UC = \frac{1}{Q_n} \cdot \sum_{t=0}^{n} C_t (1+i)^{-t} \quad (5.9)$$

where: TC = total cost

UC = unit cost

$Q_n$ = total quantity of units produced at the end of period n

It may also be useful to express Total Cost in terms of fixed and variable costs. Fixed costs do not vary in proportion to the quantity of output whereas variable costs do. The relationship is given by:

$$\mathrm{TC} = a \cdot Q_n + b \tag{5.10}$$

where: a = variable cost

b = fixed cost

or, if Equation 5.10 is divided by quantity of units produced,

$$\mathrm{UC} = a + \frac{b}{Q_n} \tag{5.11}$$

### 5.4.1 Economic Analysis Assumptions and Parameters

1. Concrete contractors' business environment is characterized by strong price competition, where contracts are awarded to the lowest bidder. Whether a general contractor or a building owner, the employer knows the market unit price for a specified quality and is unwilling to pay more than what he considers to be the 'going rate'. Hansen and Tatum (1989) have described this environment as 'reciprocal competition', in which companies compete from very similar positions relying on operating differences to obtain contracts. This suggests that increased operating costs which result from capital equipment purchases cannot be passed on to the consumer unless all firms experience the same conditions. Thus, although offering a higher quality

product at a higher operating cost, the contractor using semi-automated concrete placing cannot charge more than the going market rate for a conventional floor. However, as will be shown later, in situations where higher quality is explicitly specified, the contractor using semi-automated concrete placing can benefit from an advantage over the contractor manually.

2. Although in practice different types and sizes of slabs would be poured in one year, for the purpose of this analysis, the contractor's annual work volume is based on the construction of a number of unit slabs per year. The value of each alternative is determined for a constant annual volume of work over a four year time horizon. Such an economic horizon is seen to reflect rugged site operating conditions[11].

3. This analysis considers only those costs and benefits which are directly related to the operation and which can be allocated to its related tasks. Indirect costs, such training expenses, and indirect benefits, such as schedule compression and increased work volume, are not included in this analysis but their impact on the decision to automate will be discussed in Section 5.4.4.

4. Cash flows which occur in the last year of a project's life, such as salvage value resulting from the disposition of equipment and tax benefits resulting from disposition at a loss (or tax liabilities if disposed of at a gain), can have an important influence on a project's fixed cost component. For the purpose of this analysis, in order to avoid terminal loss, recapture, or capital gain effects on the company's taxable income, salvage value is assumed to be equal to the undepreciated capital cost of the equipment in the final year.

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11 By comparison, the lower limit of expected economic life for manufacturing robots is 5 years (Warszawski 1988).

5. In the case of the fully automated operation, sufficient experienced labour is assumed to be available, both for placing and finishing, to allow the achievement of greater production rates.

6. The hourly labour rate for floor finishers as of May 1991 is given in Table 5.6, and represents the gross wage rate plus all benefits and contributions. Apprentice finishers must undergo two 2000-hour training periods during which they respectively earn 70% and 85% of the tradesman's wage. For the purpose of this analysis, the apprentice's wage rate is considered to be 85% of the tradesman's. The composition and cost of crews for the different alternatives are given in Table 5.7.

7. Capital costs are given in Table 5.8. For the mechanical trowel, capital costs are well known and relatively stable, while for the laser guided screeder, capital costs are expected to decline as more units are sold. The capital cost for the robotic finisher represents an estimated average value based on discussions with Japanese developers. Potential variations in capital costs are accounted for in a sensitivity analysis.

8. Maintenance costs for all equipment are estimated based on 232,000 $m^2$ (2,500,000 $ft^2$) of operation. For power trowels, these costs were found to be very small due to their simple mechanical components, and are estimated at 2% of capital cost. Robot maintenance costs are estimated at 10% of capital costs, based on information obtained from Japanese developers. Maintenance costs for the laser-guided screeding machine, which include those related to regular maintenance and to the replacement of parts due to wear, were found to be relatively high, representing $ 40,000 or approximately 18% of capital cost.

| Item | Rate |
|---|---|
| Hourly wage rate | $ 21.67/hr |
| Vacation | $ 2.38/hr |
| Gross Hourly Wage Rate | $ 24.05/hr |
| UI contribution | $ 0.60/hr |
| Quebec pension plan | $ 0.55/hr |
| Health insurance | $ 0.90/hr |
| Fringe benefits | $ 1.76/hr |
| Insurance sales tax | $ 0.06/hr |
| Quebec construction commission | $ 0.18/hr |
| Association of building contractors | $ 0.02/hr |
| Other funds (training, indemnity) | $ 0.12/hr |
| Other (special safety) | $ 0.10/hr |
| Sub total | $ 28.34/hr |
| Quebec health & safety commission | $ 3.51/hr |
| Total Hourly Labour Rate | $ 31.85/hr |

Table 5.6: Hourly Labour Rate for Floor Finishers in Québec ("Hourly" 1990)

| Work Task | MP/MF | | | MP/RF | | | SAP/MF | | | SAP/RF | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | No. Men | Time (hrs) | Cost ($/hr) | No. Men | Time (hrs) | Cost ($/hr) | No. Men | Time (hrs) | Cost ($/hr) | No. Men | Time (hrs) | Cost ($/hr) |
| disharge concrete | 1 | 9.8 | 27.10 | 1 | 9.8 | 27.10 | 1 | 8.9 | 27.10 | 2 | 3.9 | 27.10 |
| spread concrete w shovel | 3 | 9.8 | 27.10 | 3 | 9.8 | 27.10 | 3 | 8.9 | 27.10 | 10 | 3.9 | 27.10 |
| place concrete w rake | 3 | 9.8 | 27.10 | 3 | 9.8 | 27.10 | - | - | - | - | - | - |
| lift wire mesh | 1 | 9.8 | 27.10 | 1 | 9.8 | 27.10 | 1 | 8.9 | 27.10 | 2 | 3.9 | 27.10 |
| set wet screed guide | 1 | 9.8 | 27.10 | 1 | 9.8 | 27.10 | - | - | - | - | - | - |
| screed and bullfloat | 3 | 9.8 | 31.85 | 3 | 9.8 | 31.85 | - | - | - | - | - | - |
| drive laser screed | - | - | - | - | - | - | 1 | 8.9 | 31.85 | 1 | 3.9 | 31.85 |
| screed slab edges | - | - | - | - | - | - | 2 | 8.9 | 31.85 | 3 | 3.9 | 31.85 |
| Place Concrete (total) | 12 | 9.8 | 339.45 | 12 | 9.8 | 339.45 | 8 | 8.9 | 231.05 | 18 | 3.9 | 1976.52 |
| Floating (total) | 3 | 9.8 | 99.55 | 3 | 9.8 | 99.55 | 3 | 8.9 | 99.55 | 6 | 3.9 | 191.1 |
| Troweling (total) | 3 | 9.8 | 99.55 | 1 | 11.8 | 31.85 | 3 | 8.9 | 99.55 | 1 | 5.9 | 31.85 |

Table 5.7: Crew Composition and Cost for Various Levels of Automation and for Conventional Surface Quality

| Equipment | (MP/MF) | | (MP/RF) | | (SAP/MF) | | (SAP/RF) | |
|---|---|---|---|---|---|---|---|---|
| | No. units req'd | Capital Cost/Unit ($) | No. units req'd | Capital Cost/Unit ($) | No. units req'd | Capital Cost/Unit ($) | No. units req'd | Capital Cost/Unit ($) |
| Power Floater | 6 | 2,500 | 3 | 2,500 | 6 | 2,500 | 6 | 2,500 |
| Robot Finisher | - | - | 3 | 50,000 | - | - | 3 | 50,000 |
| Laser-guided screeder | - | - | - | - | 1 | 227,500 | 1 | 227,500 |
| Truck for finish. equip | 1 | 25,000 | 1 | 25,000 | 1 | 25,000 | 1 | 25,000 |
| Truck for screed. equip | - | - | - | - | 1 | 50,000 | 1 | 50,000 |
| Total Cost | | 40,000 | | 182,500 | | 317,500 | | 467,500 |

Table 5.8: Summary of Capital Costs Associated with Various Levels of Automation

9. Equipment operation costs are estimated per unit slab (1859 $m^2$; 20,000 $ft^2$), and represent mainly the cost of fuel or electric power and hydraulic oil. For each power trowel, robot finisher, and laser-guided screeder this represents, respectively, \$ 25, \$ 50, and \$ 200.

10. Revenues are based on the going market rate for a conventional slab on grade in Montreal, i.e., approximately 5.38 \$/$m^2$ (50 ¢/$ft^2$). The combined federal and provincial tax rate is 30%, and the mandated depreciation rate is also 30%. The Minimum Attractive Rate of Return (MARR), which reflects the contractor's cost of capital, is assumed at 10%, and an escalation factor of 4% per annum is used to adjust all costs except capital costs.

### 5.4.2 Analysis Results

1. Base Case

Using the assumptions and parameters just described, Equation 5.9 is applied, and the results are shown in Figure 5.13. This Figure shows the relation between Unit Cost and the number of units produced per year, or annual production output, for the various levels of automation. Equation 5.11 is then applied for each alternative, yielding fixed and variable costs:

for MP/MF; $$UC = 1.69 + \frac{25,236}{Q_n} \qquad (5.12)$$

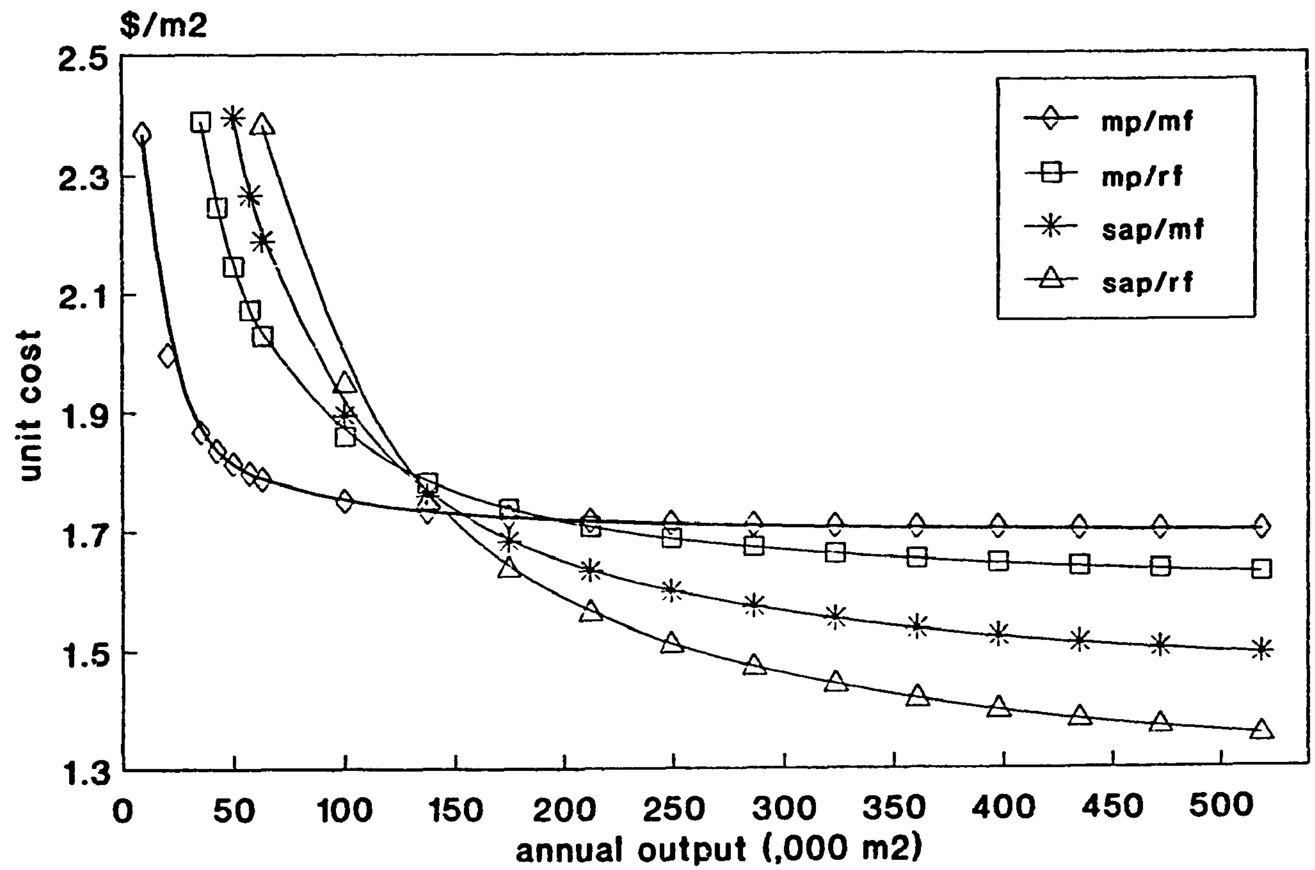


Figure 5.13: Relationship Between Unit Cost and Annual Production Output for Various Levels of Automation and Conventional Surface Quality

for MP/RF; $$UC = 1.57 + \frac{115{,}139}{Q_n} \tag{5.13}$$

for SAP/MF; $$UC = 1.40 + \frac{200{,}310}{Q_n} \tag{5.14}$$

for SAP/RF; $$UC = 1.21 + \frac{294{,}945}{Q_n} \tag{5.15}$$

The results of the analysis are summarized in Table 5.9. Clearly, the greater the volume of work undertaken, the more each level of automation will become attractive over the conventional manual operation. Specifically, Figure 5.13 shows that automation of the entire operation requires a minimum output of 142,563 $m^2$/yr (1.54M $ft^2$/yr or 77 unit slabs) to be more economical than the conventional manual operation, whereas automation of placing alone requires 150,392 $m^2$/yr (1.62M $ft^2$/yr or 81 unit slabs), and automation of finishing alone requires 194,122 $m^2$/yr (2.1M $ft^2$/yr or 105 unit slabs).

The conventional manual operation is the alternative with the lowest fixed cost, \$ 25,236, because of its low capital cost component, and the highest variable unit cost, 1.69 \$/$m^2$, because of its high labour cost component. Above an output of approximately 92,950 $m^2$/yr (1M $ft^2$/yr), there is little difference between variable and unit costs.

The automation of either finishing or placing alone offers, respectively, 6.6% and 17.2% decreases in variable unit cost compared to the conventional manual operation, but

| Benefit | Levels of Automation | | |
|---|---|---|---|
| | MP/RF | SAP/MF | SAP/RF |
| Annual break-even volume | 194,122 $m^2$ (105 unit slabs) | 150,392 $m^2$ (81 unit slabs) | 142,122 $m^2$ (77 unit slabs) |
| Variable cost reduction | +6.6% | +17.2% | +28.5% |
| Fixed cost multiplier | 4.5 | 8 | 11.7 |
| Placing crew size reduction | - | +33% | -50% |
| Finishing crew size reduction | +33% | - | -17% |
| Duration reduction (total operation) | - | +4.5% | +31% |

Table 5.9: Summary of Economic Analysis Results

requires 4.5- and 8-fold increases in fixed costs. Automation of the entire operation leads to the greatest reduction in variable unit costs compared to the conventional manual operation, 28.5%, but requires an 11.7-fold increase in fixed costs.

Of the three alternatives, automation of both placing and finishing makes possible the greatest savings in unit cost at the lowest annual output, but requires the greatest capital investment. The benefits are achieved by reducing the overall duration of the operation by 31%, in spite of the fact that crew size must be increased by 50% (6 men) during placing and by 17% (1 man) during finishing. At a break-even output of 150,392 $m^2$/yr , the automation of placing alone was found to be economical well within the actual annual output of the contractor using it. Benefits were incurred through labour savings of 33% (4 men) in the placing crew, and a reduction in operation duration of 4.5% (0.9 hrs). Automation of finishing alone is the alternative which requires the greatest annual output to be more economical than the conventional manual operation because the robot's use is assumed to be restricted to troweling and its production rate is limited by that of the manual placing operation: the benefits in this case were obtained solely by a reduction of 33% in the size of the finishing crew.

Compared to the conventional manual operation, all three alternatives become economical within a narrow range of break-even outputs, namely between 142,000 and 194,000 $m^2$. The volume of work this represents, approximately 50,000 $m^2$ or 27 unit slabs, is relatively small in proportion to the level of feasible outputs required. Whether the unit cost savings to be obtained can be justified considering the levels of production to be maintained and the investments required is a decision which each contractor must make based on the unique nature of his business. However, certain general observation about the attractiveness of each alternative can be made.

Implemented by itself, the use of the robot finisher is restricted by the production rate of the placing crew and cannot be used to its full advantage. The additional capital cost investment of $ 142,000 required, compared to the manual operation, seems high in comparison with the maximum unit cost savings of 6.6% which can be achieved.

Automation of the entire operation requires an increase in crew size which many contractors would find difficult to achieve, even though this increase may not be as large as the one estimated in this analysis because as larger crews are assembled, placing productivity may increase beyond that indicated by Equation 5.2. Also, comparing this alternative with the automation of placing alone, which results in decreased crew size, affords a $ 150,000 reduction in capital cost investment, and requires an increase in break-even output of only 7,829 $m^2$, or approximately 4 unit slabs, indicates that some contractors may find automation of both placing and finishing difficult to justify.

2. Sensitivity Analysis

In order to determine the effect of variations in base case parameters on the feasibility of the different levels of automation, a sensitivity analysis is performed. Figure 5.14 illustrates the effect of variations in the labour cost, normalized and expressed as percentage variation from the base case, on the annual output that is required for each level of automation to be more economical than the conventional manual operation. For example, a 10% increase in labour cost from the base case, represented by the normalized

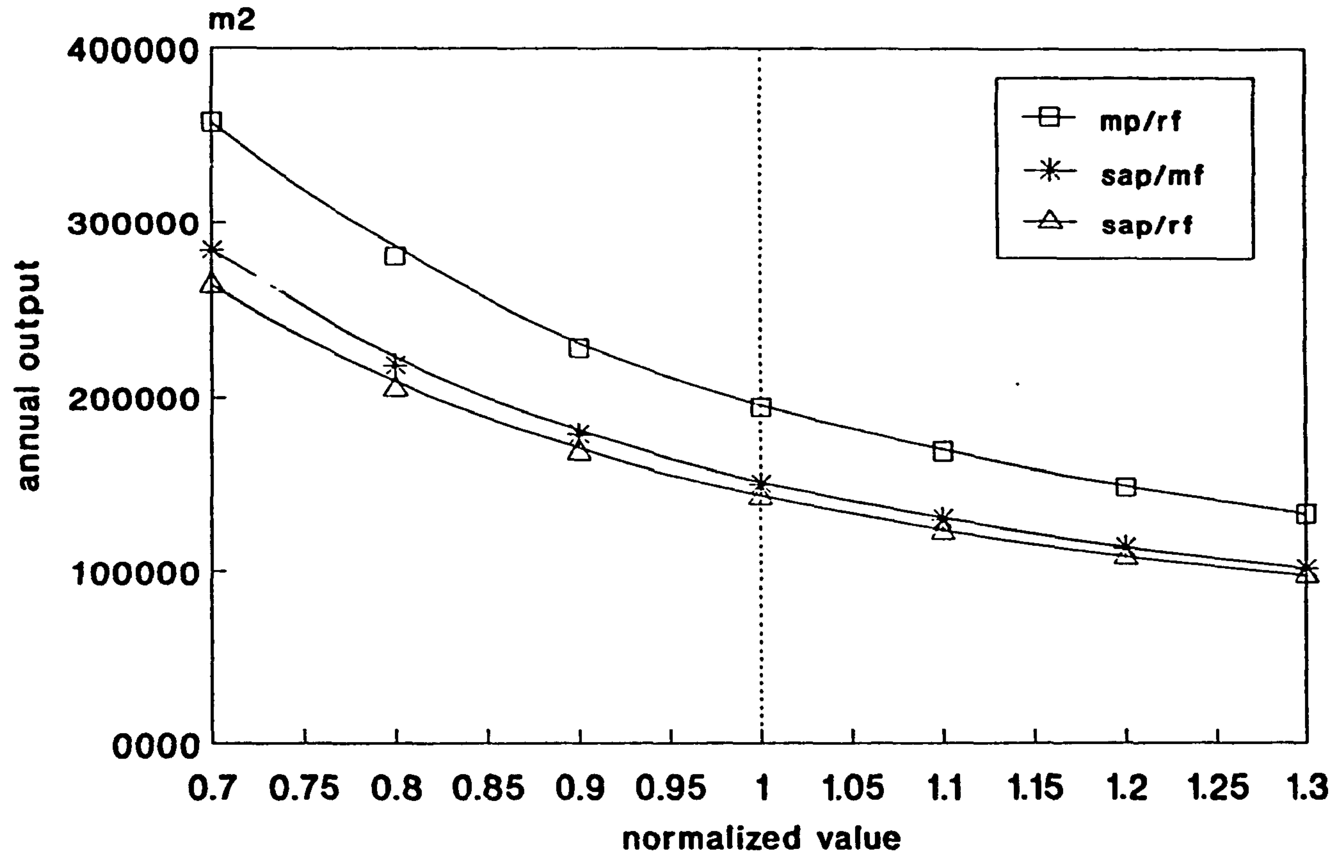


**Figure 5.14: Effect of Labour Rate Variations on Annual Break-Even Output**

value of 1.1, reduces the annual break-even output by approximately 13% for each alternative. Additional labour cost increases have a similar but smaller effect on the break-even output of each alternative.

Figure 5.15 shows the effects of capital cost variations, normalized and expressed as percentage variation from the base case, on the annual output that is required for each alternative to be more economical than MP/MF. Thus, each 10% increase in the cost of the robot finisher alone would increase the annual output required for its use to be more economical than MP/MF by 26,883 m2, or approximately 15 unit slabs, while each 10% increase in the cost of the semi-automated screeding machine alone would increase its break-even outpu. by 16,200 m2 or 9 unit slabs. In the case of the fully automated operation, each 10% increase in capital cost would increase the break-even output by 16,600 m2 or 9 unit slabs.

Figure 5.16 shows the effects of variations in the Minimum Attractive Rate of Return, normalized and expressed as percentage variation from the base case, on the annual output that is required for each alternative to be more economical than MP/MF. Variations in MARR have a small and similar effect on the required break-even output of each alternative. For example, each 1% increase in MARR increases the break-even output by approximately 4% for all three alternatives.

It must be noted that automation of finishing alone was found to be quite sensitive to capital cost. For example, a minimum 16% decrease in the capital cost of the robot finisher, from 50,000 $/unit to at least 42,000 $/unit, would make that alternative more attractive than the automation of placing alone. In general, allowing for a possible 30%

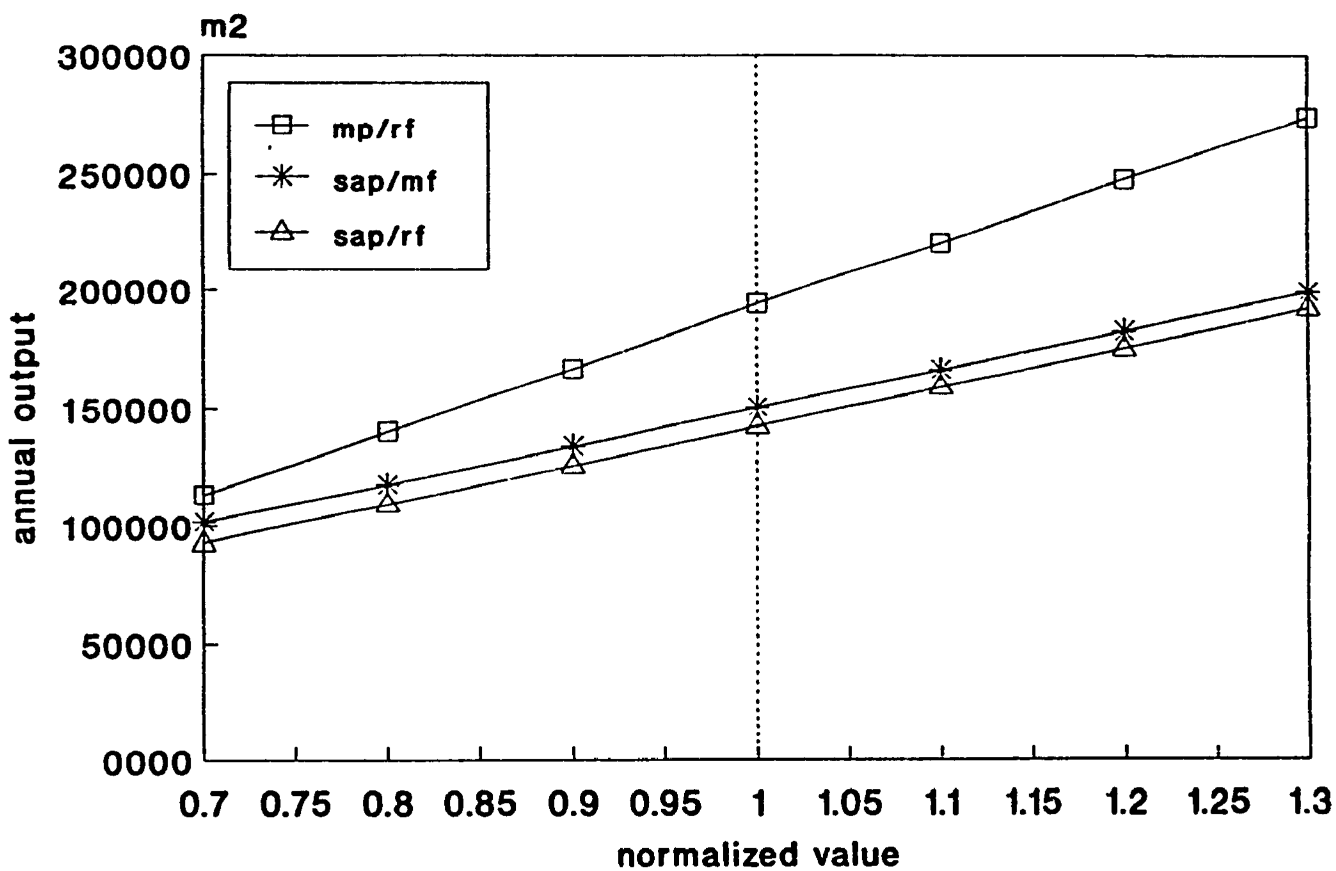


Figure 5.15: Effect of Capital Cost Variations on Annual Break-Even Output

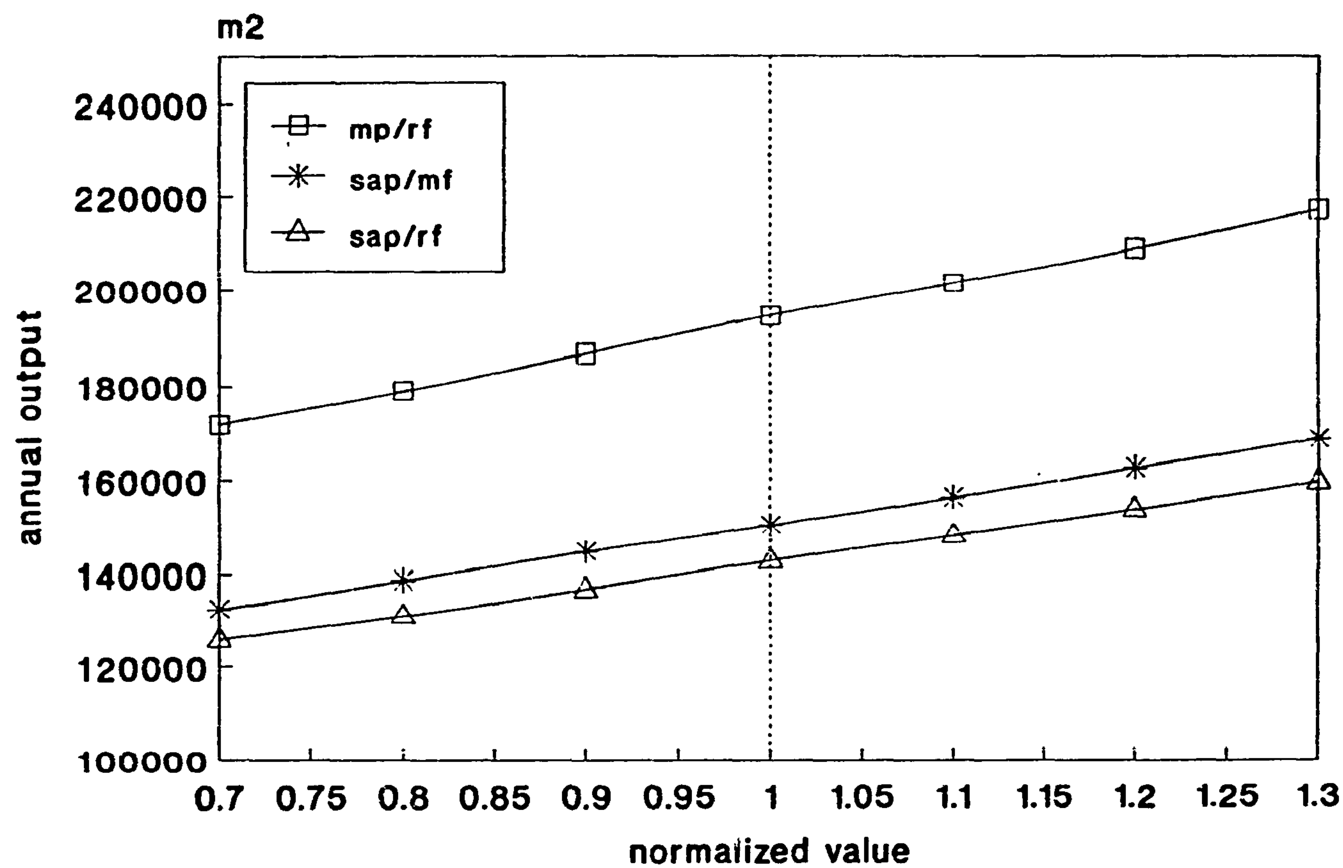


Figure 5.16: Effect of MARR Variations on Annual Break-Even Output

variation in either labour cost, capital equipment cost, or MARR, none of the alternatives to conventional manual construction would be attractive to the smallest concrete contractor participating in this study. The medium-large firms would certainly find the required investment and work volume less difficult to achieve.

### 5.4.3 Quality Considerations

A main factor in this analysis is that unless a client explicitly specifies a high surface quality slab, the contractor is unable to charge for the quality improvements resulting from automated placing because of reciprocal competition. What would be the attractiveness, however, of the various alternatives if quality improvements were explicitly recognized? More specifically, how would the unit cost of each alternative be affected if compared with that of manually constructing a slab to meet the same surface quality requirements that are achievable by semi-automated placing?

In order to answer this question, the construction of a unit slab is analyzed based on the same parameters as the base case conventional slab of the previous section, but taking the following factors into account:

1. The surface quality of the unit slab is $F_f45/F_l30$. This represents, as indicated in Section 5.2.2, an average surface quality which can be achieved by semi-automated placing.
2. As shown in Section 5.1.3, in order to meet the target surface quality, the unit slab must be constructed in strips of 6.1 m (20 ft) width or less, and requires at least 3

corrective re-straightedgings. Thus the unit slab is constructed by pouring alternating 6.1 m x 62 m (20 ft x 200 ft) strips, with three strips poured on the first day and the remaining two on the following day (as shown Figure 5.17).

3. Screeding is achieved by drawing a truss-mounted vibrating straightedge over the entire length of the strip. The capital cost of the vibrating straightedge and side rails is 10,000 \$, and its maintenance and operation costs are assumed to be negligible. According to contractors interviewed having experience with this method, a production rate of 25 $m^3$/hr is assumed. The composition and cost of the crews required for the various levels of automation are given in Table 5.10. The Table also indicates the estimated crew requirements for placing, leveling, and removing side forms.

Using the parameters and assumptions just described, Equation 5.9 is applied, and the results are shown in Figure 5.18. Equation 5.10 is then applied for each alternative, yielding fixed and variable costs:

for MP/MF; $$UC = 2.18 + \frac{33,536}{Q_n} \qquad (5.16)$$

for SAP/MF; $$UC = 1.50 + \frac{200,310}{Q_n} \qquad (5.17)$$

for SAP/RF; $$UC = 1.31 + \frac{294,945}{Q_n} \qquad (5.18)$$

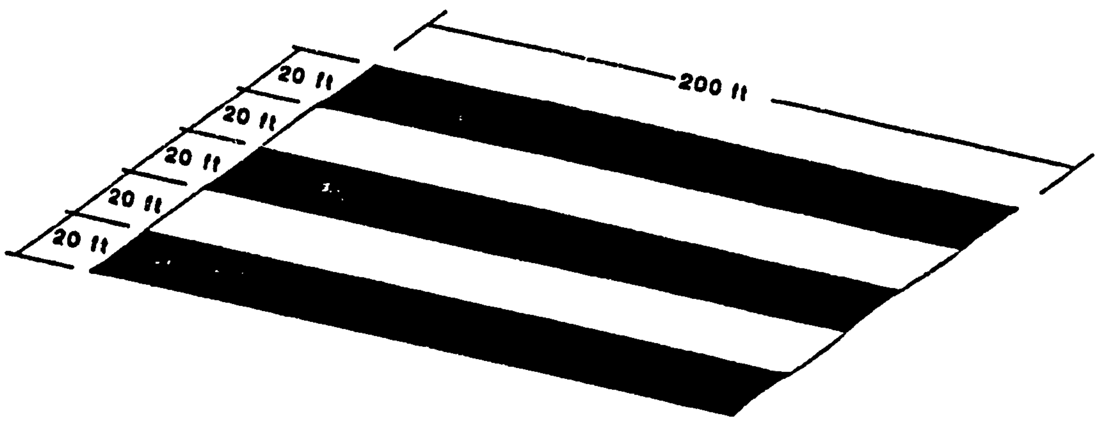


Figure 5.17: Narrow Strip Construction Sequence

| Work Task | MP/MF | | | | SAP/MF | | | SAP/RF | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | No. Men | Time day 1 (hrs) | Time day 2 (hrs) | Cost ($/hr) | No. Men | Time (hrs) | Cost ($/hr) | No. Men | Time (hrs) | Cost ($/hr) |
| carpenter | 1 | 7.5 | 2.5 | 30.48 | 1 | 4 | 30.48 | 1 | 4 | 30.48 |
| labourer | 3 | 7.5 | 2.5 | 25.91 | 2 | 4 | 25.91 | 2 | 4 | 25.91 |
| Forming (total) | 4 | 7.5 | 2.5 | 108.21 | 3 | 4 | 82.3 | 3 | 4 | 82.3 |
| disharge concrete | 1 | 6.8 | 4.5 | 27.10 | 1 | 8.9 | 27.10 | 2 | 3.9 | 27.10 |
| spread concrete with shovel | 3 | 6.8 | 4.5 | 27.10 | 3 | 8.9 | 27.10 | 10 | 3.9 | 27.10 |
| pull vibrating straightedge | 3 | 6.8 | 4.5 | 27.10 | - | - | - | - | - | - |
| lift wire mesh | 1 | 6.8 | 4.5 | 27.10 | 1 | 8.9 | 27.10 | 2 | 3.9 | 27.10 |
| drive laser screed | - | - | - | - | 1 | 8.9 | 31.85 | 1 | 3.9 | 31.85 |
| screed slab edges | - | - | - | - | 2 | 8.9 | 31.85 | 3 | 3.9 | 31.85 |
| Place concrete (total) | 8 | 6.8 | 4.5 | 216.8 | 8 | 8.9 | 231.05 | 18 | 3.9 | 1976.52 |
| Corrective re-straightedging (total) | 3 | 6.8 | 4.5 | 95.55 | - | - | - | - | - | - |
| Floating (total) | 3 | 6.8 | 4.5 | 95.55 | 3 | 8.9 | 95.55 | 6 | 3.9 | 191.1 |
| Troweling (total) | 3 | 6.8 | 4.5 | 95.55 | 3 | 8.9 | 95.55 | 1 | 5.9 | 31.85 |

Table 5.10: Crew Composition and Cost for Various levels of Automation for High Surface Quality

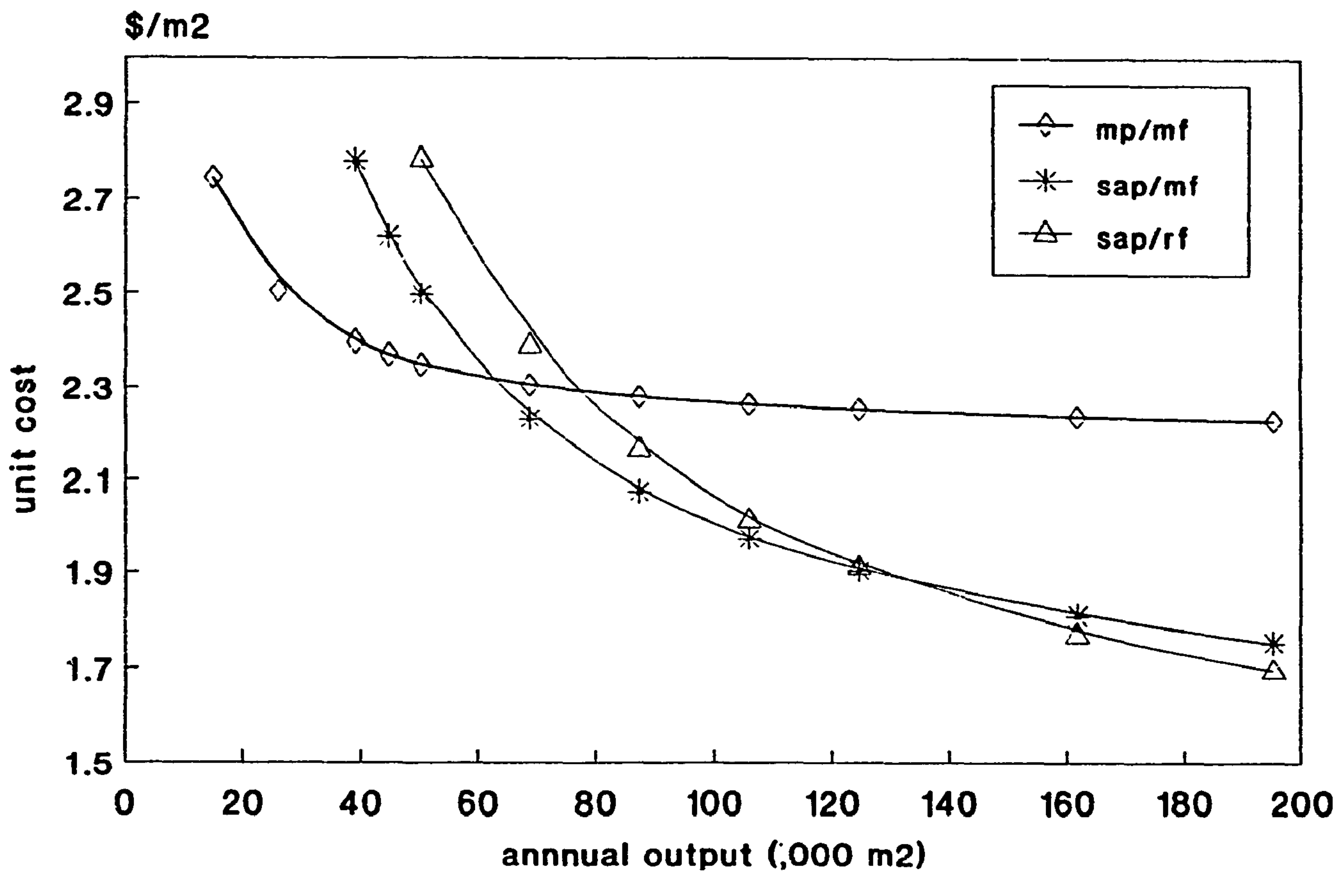


**Figure 5.18: Relationship Between Unit Cost and Annual Production Output for Various Levels of Automation and High Surface Quality**

Figure 5.18 indicates that when comparing slabs of similar high quality, manual construction is the alternative with the lowest unit cost for yearly outputs of up to 61,076 $m^2$/yr (657,000 $ft^2$/yr or 33 unit slabs). Between 61,076 $m^2$/yr and 130,000 $m^2$/yr (1.4M $ft^2$/yr or 70 unit slabs), automation of placing alone is the alternative yielding the lowest unit costs. Above 130,000 $m^2$/yr, automation of the entire operation is the most attractive alternative, even though it offers lower unit costs than the manual operation starting at 75,588 $m^2$/yr (813,000 $ft^2$/yr or 41 unit slabs).

It is clear that taking quality into account has a significant positive effect on the attractiveness of automation. For example, when quality is considered, both SAP/MF and SAP/RF allow a reduction in operation duration from 11.3 hours over 2 days to, respectively, 8.9 hours and 3.9 hours. Additionally, the output required for the automation of placing alone to be more advantageous than manual construction is 59% less than the output required when quality is not considered. Similarly, with respect to the automation of the entire operation, break-even output is reduced by 47% when quality is considered compared to when it is not. Also, potential unit cost reductions of both alternatives are more significant when quality is specified than when it is not: however, unit cost reductions between the alternatives may not be enough to justify the additional investment required.

Figure 5.19 shows the relationship between unit cost and output levels for the various alternatives and for both normal and high quality manual construction. Although the shapes of the curves may vary depending on the assumptions modified, the figure generally shows that semi-automated placing offers the potential for significantly more unit cost savings when the cost of quality is considered compared to when it is not, and

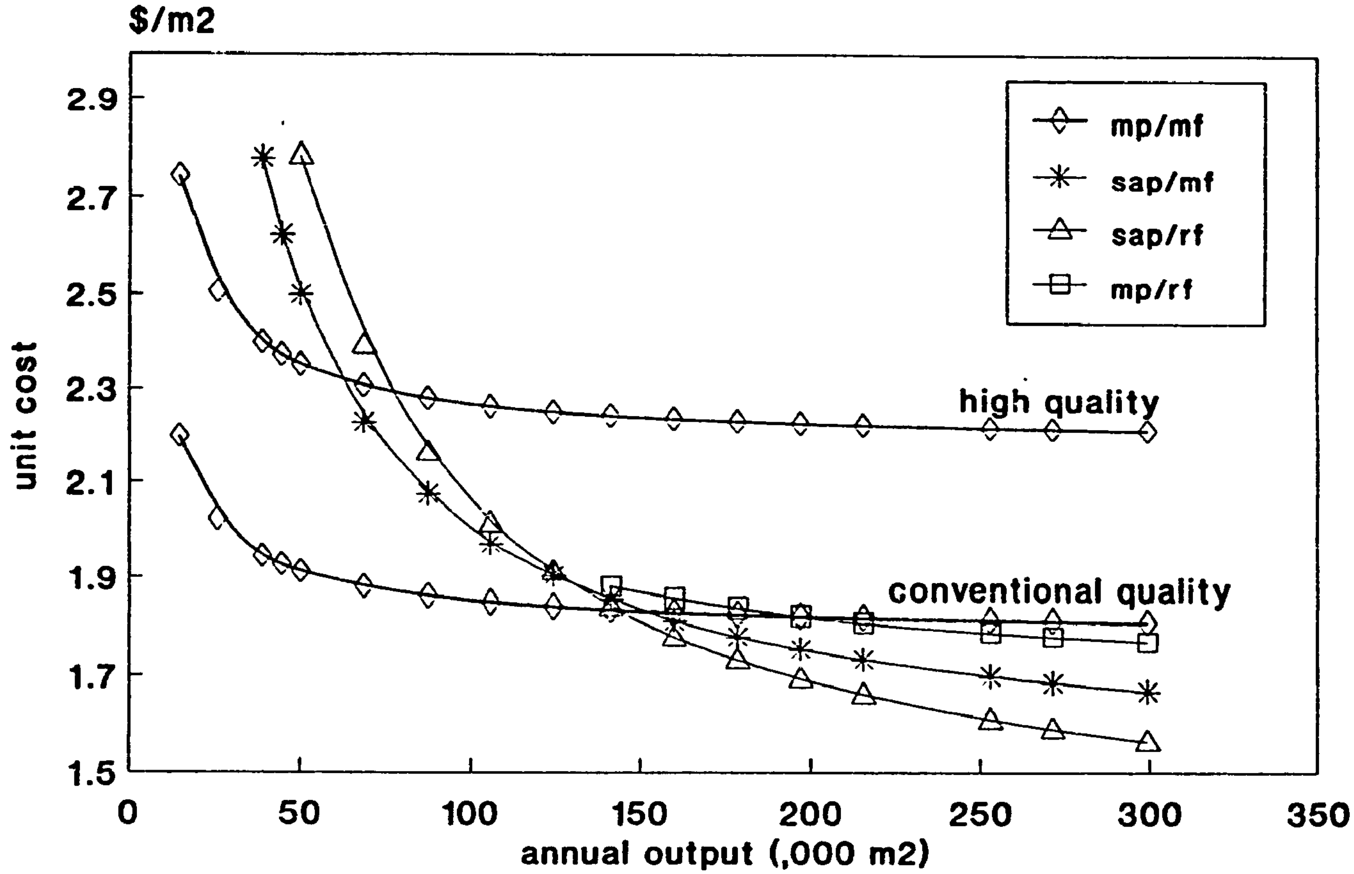


Figure 5.19: General Relationship Between Unit Cost, Annual Production Output, and Quality for Various Levels of Automation

that the use of the robot finisher alone does not offer significant unit cost savings. Even if, as was shown in the previous section, its capital cost would be reduced, shifting the MP/RF curve in Figure 5.19 to the left beyond the SAP/MF curve, the range of unit cost savings would not increase appreciably. Such a capital cost reduction would, however, also shift the SAP/RF curve to the left , making it, perhaps, more attractive than SAP/MF compared to both normal and high quality construction.

### 5.4.4 Additional Factors

The economic feasibility of automation must consider all costs and benefit in order to yield valid results. In manufacturing, for example, the cost of implementing a robot is, typically, two and a half times the base machine cost due to plant modification, programming, and system integration needs (Ayres et al. 1985). This cost is further increased where the product must be redesigned and labour retrained.

Although, due to the simple nature of the operation analyzed in this study, these factors are not relevant, many would need to be explicitly considered in more complex construction applications. For example, programming the robot finisher is a simple task which requires entering a number of parameters, and is assumed to be performed by the job supervisor. However, in operations which require painting surfaces or placing and/or attaching discrete objects, set-up, programming, and debugging costs can be expected to be quite significant.

Since construction workers have no experience with robots, training costs must also be considered. In this study, for example, it was found that an inexperienced worker requires 2 to 3 years of training before obtaining the necessary skills to be considered a qualified finisher. Although both the robot finisher and semi-automated screeder also require training, it can be expected to be significantly less than what is required for the manual task[12]. Thus, in this case, considering training costs in the cost of labour, would have a net positive effect on the attractiveness of the automated alternatives. However, this is not expected to be the case for all construction applications.

Automation also affords indirect benefits, which, although difficult to evaluate quantitatively, must be considered in the decision to automate. For example, the potential use of automation year round on Canadian construction sites may offer a significant advantage considering that the productivity of many trades drops by at least 20-30% when temperatures fall below 0°C (or rise above 32°C) (Adrian 1987). The potential for reducing overtime is also an important benefit of automation, since overtime work commands an increased labour rate and, often, reduces labour productivity (Warszawski 1984).

For the application considered in this study, material savings could be an important indirect benefit of automation. For example, it was found to be common practice for construction managers to charge subgrade and concrete contractors for the difference between the amount of concrete actually used to pour a slab and the amount specified in the plans. Excess concrete would be required, for example, due to poor subgrade and/or

12 In fact, for the laser guided screeder, a one week training period is offered (included in the capital cost of the equipment), after which the operator is considered to be efficient.

surface flatness and levelness. The use of laser-guided grading by the subgrade contractor and laser-guided screeding by the concrete contractor could result in better control of surface tolerances and of the quantity of concrete required.

Operation duration reduction is another important indirect benefit, since it can not only help the concrete contractor by allowing him to reduce labour costs but may also benefit the general contractor by allowing him to compress the building's overall construction schedule. The ability to compress total schedule is an important advantage and can lead to monetary bonuses and an increase in the volume of work. Other factors can also help the concrete contractor increase his business volume, such as increased production rates and productivity and the efficient redistribution of his workforce on projects which are unsuitable for automated equipment. Also, while he may not be able to charge for increased quality, the recognition that he can deliver a higher quality product compared to manual construction may improve his marketability and his capacity to attract repeat business.

### 5.5 Summary and Conclusion

This section presents a summary of the methodology employed in the conduct of the study and general conclusions regarding the implementation of automation.

### 5.5.1 Summary of the Methodology

In order to analyze the factors which can influence the implementation of automation in construction operations, the construction of concrete slabs on grade was selected as a case study because currently available technologies for this operation, namely semi-automated placing and robotic finishing equipment, enable the achievement of this objective with a minimum of speculation and reasonable accuracy.

The analysis was conducted through a review of the pertinent literature and field research. Five specialized concrete contractors agreed to participate and, through structured interviews with representatives of each, information was collected to provide the basis of this case study. These interviews were supplemented by 3 on-site visits per contractor allowing observation of task performance. This method was chosen because obtaining representative data from site observations was not considered feasible and because it was felt to be best suited to evaluate technologies which are not yet in actual use by allowing maximum interaction with the contractors.

From the data gathered, construction methods and practices are identified, and productivity, quality, and economic analyses are performed. Although only five specialized local contractors -with only one using semi-automated placing- participated in the study, it is clear from the consistency of the feedback received that the data help establish clear trends. Thus, although not meant to provide absolute results, this study identifies many of the practical implications contractors must consider in implementing automation in construction operations.

### 5.5.2 Conclusion

The analysis presented in this chapter provides evidence that concrete contractors can achieve positive results by implementing automation and robotics in their operations. In view of the current state of technology however, contractors will have to combine manual, mechanized, and automated work in order to achieve their objectives. This study suggests that careful planning is required to allow the benefits of each to be fully realized. The following points are found to be central:

1. In planning for automation, focussing on the construction operation as a whole rather than on the equipment is of prime importance. Analyses which focus on the equipment instead of the operation do not anticipate the requirements which increased production rates can place on dependent tasks, and may lead to unrealistic results. This study indicates, for example, that slab on grade construction is a sequential operation necessitating a constant production rate during concrete delivery, placing, and finishing. In order to produce benefits, a production rate increase in any one operation requires a similar increase in the others.

2. Unlike many manufacturing applications where the precise production process required to manufacture a product is well established, the methods and practices used to construct buildings and their components may vary from region to region and between contractors. Thus a thorough task analysis is required in order to identify local work practices, methods, and equipment. This detailed task analysis is also required to identify the factors which have an influence on quality.

3. Market characteristics have an important influence on the implementation of automation. For example, this study found that the constraining factor in the automation of either placing or finishing was the availability of labour to increase the production rate of the dependent operation. Thus, under such constraints, since neither the robot finisher or the semi-automated screeder can be used to their full advantage, contractors must carefully determine whether the potential unit cost savings can justify the required capital investment.

   This study has also shown that contractors must be very careful in considering the simultaneous automation of dependent operations. Although, intuitively, it would seem that this would reduce labour requirements, in this analysis of concrete slab-on-grade construction it was found to have the opposite effect. This is because since neither placing or finishing are completely automated, both require labour to work in conjunction with the automated equipment at higher production rates. Thus, it is not only important to consider the effect of increased production rates on dependent operations, but also on the operations themselves if automated with human support.

4. Although automation may lead to quality improvements, market characteristics such as reciprocal competition may not allow contractors to charge for increased costs unless higher quality is explicitly specified. Thus, although offering a higher quality product at a higher cost, the contractor using the laser-guided screeding machine cannot charge more than the going market rate for a conventional floor. The benefits of automated equipment in this case are seen to provide the contractor with a competitive advantage by allowing him to generate more work by attracting clients through the promise of a higher quality slab at no extra cost.

When bidding, however, on a floor which explicitly specifies high surface quality, the contractor using automated placing would benefit from a distinct advantage over contractors who base their bids on conventional manual construction. In this case study, it was found that when higher quality is specified, automation of placing alone requires 59% less annual work to be economical than when quality is not specified. Similarly automation of both placing and finishing requires 47% less work.

5. Automation offers many indirect benefits and costs which, although difficult to evaluate quantitatively, must be considered qualitatively in the decision to automate. In this study, it was found that important indirect benefits to consider include material savings, schedule compression, and increased volume of work.

6. High costs were found to be the most important barrier to automation in this study, followed by disruption of traditional working practices and complexity of equipment. Although the last two factors were not found to be significant, the potentially high costs were. Allowing for a possible 30% variation in either capital cost, labour cost, or MARR, none of the alternatives to conventional manual construction would be attractive to the smallest concrete contractor participating in this study. The minimum investment required for automation corresponds to more than 4 times that required for the conventional manual operation, and represents approximately 36% of the smallest contractor's operating revenues. The maximum investment required for automation represents more than 11 times that required for the conventional manual operation, and accounts for 31% of the largest contractor's operating revenues.

Automation can decrease unit costs provided that annual output can be maintained at high levels in order to spread the increased capital costs over larger volumes of output. For the automation of placing and finishing alone, the small savings in unit cost achieved at high levels of output threaten serious disadvantages if such conditions are not met due to, for example, cyclical or seasonal fluctuations. When comparing slabs of similar quality, the annual output required for automation to be advantageous becomes considerably smaller but is dependent on the local demand for high quality slabs.

7. Easing labour shortages was found to be the most important motivation factor for local concrete contractors, followed by reducing labour costs and improving quality. Comparing these expected benefits of automation with the benefits estimated in this study suggests that although automation can help contractors in becoming more competitive, careful planning is required to ensure that unrealistic expectations do not lead to unexpected results.

# CHAPTER VI

# CONCLUSION

## 6.1 Summary and Conclusions

This thesis has addressed the feasibility and implementation of automation and robotics in Canadian building construction operations. Its major contributions correspond to its initial objectives. The first is a comprehensive review of the field of construction automation, covering R&D approaches adopted by different countries, current hardware and software developments, and studies that have been carried out to evaluate feasibility and implementation potential.

The review has shown that while considerable attention has been focussed on hardware and software developments and on the prioritizing of research efforts, relatively little attention has been paid to the efficient implementation of automated and robotic equipment by contractors. Additionally, since most efforts have focussed on robots, many studies which have addressed feasibility issues have only considered the feasibility of the robotic equipment rather than the feasibility of automating the operation.

This is an important distinction because, from the end-user's point of view, the choice of technology to perform an operation depends not only on whether it allows cost savings, but also on other factors such as its integration with other operations and its production capacity. Thus, the view adopted by this thesis that the implementation of construction applications of automation must consider that different levels of automation, i.e., manual, mechanized, semi-automated, and fully automated, may have to be combined within a particular operation, without requiring dependent operations to be of equal level of automation, but allowing the benefits of each to be fully realized.

The second contribution is the identification of the capabilities and limitations of current automation and robotic equipment, based on a survey of automated and robotic equipment developed to date and on a comparative assessment of industrial and construction robotics technologies.

It has been shown that conventional programmed automation based on positional control provides sufficient capability for the execution of a narrow range of functions within certain simple and repetitive light construction operations. These operations include those that involve surface treatment, such as floor finishing and spray painting or fireproofing, those that involve positioning discrete objects, such as ceiling panel positioning and cement bloc laying, and those that require both positioning and attaching discrete objects such as metal stud and gypsum panel erection. However, conventional programmed automation does not provide enough flexibility for dealing with the simplest variations encountered in normal field conditions.

With respect to heavy construction operations, most applications have developed as modified construction equipment, the level of control of which typically permits the extension, amplification, and/or optimization of human performance. Such applications include laser-guided grading and remote controlled excavation. Experimental applications of adaptive control have also been demonstrated for certain heavy construction operations such as excavation, but still require considerable research before being practicable to real environments.

The most important technological factors that must be addressed in order to advance the application of automation and robotics in building construction operations are: (1), the ability to program a robot independently of its working location; (2), The ability to create and update models of the environment based on sensor information; (3), The need for a central project control system that contains as-designed and as-built information and that can control multiple automated devices; (4), the mechanics and control of vehicle-manipulator combinations; and (5), design for automated construction.

The third contribution is the identification of factors that have an influence on how automation and robotics technologies can be implemented in building construction operations so that contractors can gain immediate benefits from their use. A methodology for analyzing the implementation of automation in construction operations was developed, based on the previously defined concept that manual, semi-automated, and fully automated tasks must be combined to achieve overall objectives. The methodology consists of: (1) operational analysis, where detailed task, quality and productivity analyses are performed, establishing standard work methods and levels of quality and productivity for the manual and automated tasks; (2), simulation, where a model of the operation is developed and daily production cycles determined for each alternative; and (3), economic analysis, where unit costs and production volumes are analyzed for the different alternatives and for various levels of quality.

The construction of concrete slabs-on-grade was selected as a case study operation, and the levels of automation included semi-automated placing and robotic finishing, implemented either separately or jointly. This operation was selected because the resources available to carry it out allow the full investigation of construction automation related concepts developed in this thesis with a minimum of speculation and reasonable accuracy.

Information on current industry practices relating to manual and semi-automated concrete placing and manual finishing in the Montreal area was obtained through structured interviews with five concrete contractors specializing in slabs on grade and observations of their placing and finishing crews. This method was chosen because obtaining representative data from site observations alone was not cnsidered feasible and because it was felt to be best suited to evaluate technologies which are not yet in actual use by allowing maximum interaction with the contractors. Information on robotic floor finishing, since it is not yet in use in North-America, was obtained through published reports and discussions with Japanese contractors.

This study had one important limitation, resulting from the fact that only five Montreal area firms participated in it, with only one firm using semi-automated placing equipment. However, the concern about being able to generalize from the small sample size to the population of contractors was alleviated by: (1), the fact that the sample included some of the largest and most experienced contractors from an actual population of contractors specializing in slabs on grade which is relatively small; (2), the consistency of the information collected; and (3), the fact that the study is not meant to provide absolute results but rather to identify important factors to be considered in the decision to automate.

In general, this study provided evidence that contractors can achieve positive results by implementing automation and robotics in their operations. However, comparing the generally acknowledged benefits of automation with those observed to occur in this study suggests that although automation can help contractors become more competitive, careful planning is required to ensure that unrealistic expectations do not lead to unexpected results. In general, the following factors were found to be important in successfully implementing automation:

1. Construction automation does not necessarily lead to reduced manpower requirements.
   This thesis has already shown that the current level of technology allows the automation of certain functions within simple and repetitive tasks. This suggests that in many tasks, human operators will need to either share work cycles with automated equipment, such as in semi-automated concrete placing, or, complement automated equipment by performing that part of the task which requires judgement, such as in robot finishing. Thus, as long as automated and robotic equipment automate only part of a task, the manual labour requirements needed to automate the other part(s) may or may not lead to reduced overall manpower requirements.
2. Labour availability constraints have an important influence on the feasibility of automation.
   Under labour availability constraints, automation is not feasible if the manpower required to support the automated task exceeds that which is available to the contractor.

If manpower requirements can be met, or are reduced, then the feasibility of automation depends on whether sufficient manpower is available to increase the capacity of the dependent task(s) to absorb the increased output. If it is not, then automated and robotic equipment cannot be used to their full potential.

3. Quality improvements which may result from automation do not always yield direct benefits.

   Market characteristics such as reciprocal competition restrict the ability of contractors to gain direct benefits from improvements in quality, unless these improvements are explicitly specified. However, quality improvements do offer important indirect benefits, namely, by increasing the capacity to attract repeat business through the promise of higher quality at no added cost. In cases where higher quality is explicitly specified, contractors using automation may benefit from significant direct savings over ones working manually.

4. Labour cost reductions must be considered along with other consequences of automation in the decision to automate.

   Contractors cannot rely solely on labour cost reductions to justify automation. Although in all the cases considered in this analysis total labour costs resulting from automation were reduced, in some cases the size of the crew required to support automation increased as a result of the need to maintain higher productivity rates. Such increases may not be feasible if the availability of labour is limited.

## 6.2 Future Research Needs

Construction automation and robotics is a relatively new field, and, consequently, considerable research is still required before significant commercial applications occur. The area of implementation studies, in particular, is one which has received little attention, and one which is critical to the success of potential applications. The analysis presented in this study, although based on a relatively simple application and obviously not all-inclusive, permits drawing important conclusions regarding the factors which contractors must consider in order to gain immediate benefits from current automated and robotic equipment.

The concepts developed in this thesis should be incorporated in more comprehensive studies aimed at developing: (1), a generalized methodology for assessing the economic consequences of implementing automation and robotics in construction operations that includes all direct, indirect, and strategic (non-monetary), benefits an costs; (2), a decision support system for choosing between different levels of automation under multiple contractor objectives, (3), guidelines for the modification or redesign of traditional construction operations to make them more amenable to automation. The issues addressed in this thesis also have important consequences for the design of automated and robotic equipment. Important work needs to be done on the establishment of design criteria and parameters for various construction tasks based on realistic production targets and the most efficient use of human support.

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## APPENDIX A

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## APPENDIX B: MicroCYCLONE Program Listing

```
---------------------------------------------------------------------------
                          *** NETWORK FILE ***
---------------------------------------------------------------------------
LINE     1 : NAME 'SLAB ON GRADE CONSTRUCTION' LENGTH 1440
             CYCLE 83
LINE     2 : NETWORK INPUT
LINE     3 : 1 QUE 'NEW TRUCK AVAILABLE' GEN 3
LINE     4 : 2 COMBI SET 1 'POSITION TRUCK' PRE 1 6 35 FOL 3
LINE     5 : 3 QUE 'TRUCK READY'
LINE     6 : 4 COMBI SET 2 'SPREAD CONCRETE'PRE 3 8 FOL 5 6 7 32
LINE     7 : 5 FUN CON 3 FOL 1
LINE     8 : 6 QUE 'POSITION PERMIT AVAILABLE'
LINE     9 : 7 NORMAL 'SCREED CONCRETE'SET 3 FOL 8 9
LINE    10 : 8 QUE 'CREW AVAILABLE'
LINE    11 : 9 NORMAL 'WAIT CONCRETE FIRST SET' SET 4 FOL 10 15
LINE    12 : 10 NORMAL 'WAIT 60' SET 5 FOL 11 17
LINE    13 : 11 NORMAL 'WAIT 60' SET 6 FOL 12 19
LINE    14 : 12 NORMAL 'WAIT 60' SET 7 FOL 13 21
LINE    15 : 13 NORMAL 'WAIT 60' SET 8 FOL 14 23
LINE    16 : 14 NORMAL 'WAIT 60' SET 9 FOL 25
LINE    17 : 15 QUE 'SURFACE READY'
LINE    18 : 16 COMBI SET 10 'FLOAT 1' PRE 15 27 FOL 27
LINE    19 : 17 QUE 'SURFACE READY'
LINE    20 : 18 COMBI SET 11 'FLOAT 2' PRE 17 27 FOL 27
LINE    21 : 19 QUE 'SURFACE READY'
LINE    22 : 20 COMBI SET 12 'FLOAT 3' PRE 19 27 FOL 27
LINE    23 : 21 QUE 'SURFACE READY'
LINE    24 : 22 COMBI SET 13 'TROWEL 1' PRE 21 28 FOL 28
LINE    25 : 23 QUE 'SURFACE READY'
LINE    26 : 24 COMBI SET 14 'TROWEL 2' PRE 23 28 FOL 28
LINE    27 : 25 QUE 'SURFACE READY'
LINE    28 : 26 COMBI SET 15 'TROWEL 3' PRE 25 28 FOL 28 29
LINE    29 : 27 QUE 'FLOATING CREW AVAILABLE'
LINE    30 : 28 QUE 'TROWELING CREW AVAILABLE'
LINE    31 : 29 FUN COUNTER FOL 30 QUAN 1
LINE    32 : 30 FUN CON 83 FOL 31
LINE    33 : 31 QUE 'STOP FINISHING'
LINE    34 : 32 FUN CON 83 FOL 33
LINE    35 : 33 QUE 'STOP PLACING'
LINE    36 : 34 COMBI SET 16 'WAIT DAY' PRE 31 33 FOL 35
LINE    37 : 35 QUE  'START NEW DAY CYCLE' GEN 83
LINE    38 : DURATION INPUT
LINE    39 : SET 1 1
LINE    40 : SET 2 1
LINE    41 : SET 3 2
LINE    42 : SET 4 240
LINE    43 : SET 5 60
```

## MicroCYCLONE Program Listing (Cont'd)

```
LINE    44 : SET 6 60
LINE    45 : SET 7 60
LINE    46 : SET 8 60
LINE    47 : SET 9 60
LINE    48 : SET 10 3
LINE    49 : SET 11 3
LINE    50 : SET 12 3
LINE    51 : SET 13 3
LINE    52 : SET 14 3
LINE    53 : SET 15 3
LINE    54 : SET 16 480
LINE    55 : RESOURCE INPUT
LINE    56 : 1 AT 1
LINE    57 : 1 AT 6
LINE    58 : 1 AT 8
LINE    59 : 1 AT 27
LINE    60 : 3 AT 28
LINE    61 : 1 AT 35
LINE    62 : ENDATA
```