A Comparison of Construction Automation in Major Constraints and Potential Techniques for Automation in The United States, Japan, and Taiwan

by

Jen-Chi Hsiao

Submitted to the Department of Civil and Environmental Engineering
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Abstract

The investment in construction automation is tremendous. and the duration of the benefit return is long. Therefore, those who develop construction automation must determine how to identify the potential techniques for automation and search the major constraints in order to reduce the risk of investment in construction automation. This thesis reviews issues facing the construction industries in the US, Japan, and Taiwan, and compares current automation feasibility analysis methodologies.

For searching major constraints and identifying high potential techniques, sixteen basic constraints have been selected, and a new feasibility analysis methodology has also been suggested. Both of these have been included in a questionnaire sent to all the three countries. Based on the result of this survey, the major constraints and appropriate techniques for automation are compared.

Due to the recession of the whole industry, insufficient government funding for developing CA, the particular nature of the construction industry, and the change of the policies such as the bidding system, "risk of unstable future market" has been found as the major constraint among all these three countries. Because the strong demand for accurate survey in construction and the great near term availability of a particular support technology, survey-control technique is identified as the most potential technique for automation.

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CHAPTER 1

INTRODUCTION

1.1 RESEARCH PROBLEM

Construction has always been a highly labor-intensive industry. Labor usually accounts for at least 25% of the total cost of each project.[1] This is because hourly wages for construction labor are higher than those in most other industries.[2] In spite of this, the construction industries in the United States, Taiwan and Japan are challenged by a serious labor shortage.

In the United States, construction companies are beginning to be concerned about a potential labor shortage caused by demographic changes and an aging construction work force.[3] An increasing demand for infrastructure development projects in Taiwan has created a labor shortage for 95% of local contractors. In Japan, the shortage of skilled construction workers has continued to increase since 1985 and reached 4.5% by 1990.

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[1] Tucker, R. "High Payoff Areas for Automation Applications", Proceedings of the 5th International Symposium on Robotics in Construction, June 6-8, 1988,P. 9-16.
[2] Demsetz, Laura A, "Task Identification and Machine Design for Construction Automation", Feb. 1989, p. 78-81
[3] Moore, Walt. "Construction Robotics: Removing Danger and Drudgery from Your Jobs", Construction Equipment, July 1991, P. 26-34

Also, construction remains one of the most hazardous ways to earn a living. The rate of construction accidents in Taiwan has been one of the highest of all industrial accidents. According to the U.S. Dept. of Labor's Bureau of Labor Statistics, 565 workers were killed in 1993. The construction industry accounted for 9% of all fatalities in the U.S.[4] Construction in Japan accounted for 29.3% of all industrial accidents in 1989, and 4.2% of all fatalities. It has been estimated that over 6% of total project costs are due to construction accidents.[5] Therefore, an improvement in construction safety could not only reduce accidents but also decrease the cost of the construction, and is therefore one of the most imperative goals of the construction industry.

This information indicates that in today's construction industry in the US, Japan, and Taiwan, labor shortages have to be overcome, and construction accidents must be reduced. In order to surmount these challenges, there are two approaches: first, to improve construction processes; second, to apply automation, which has had much success in manufacturing industry.

1.2 RESEARCH MOTIVATION

A study of automation in the manufacturing industry shows that manufacturing has benefited from reduced labor requirements, increased speed of production, improved quality, improved safety, reduced inventory, stabilization of work-force requirements, reduction in scrap, and improvement of company image.[6] The question is, can automation also provide the same benefits to the construction industry? Tokyo-based Shimizu Corp. says its SMART(Shimizu Manufacturing system by Advanced Robotics Technology)

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[4] Bureau of the Labor Statistics, "Occupational Injuries and Illnesses in the United States by Industry", 1993, US Department of labor

[5] Tucker, R. "High Payoff Areas for Automation Applications", Proceedings of the 5th International Symposium on Robotics in Construction, June 6-8, 1988, P. 9-16

[6] Demsetz, Laura A., "Task Identification and Machine Design for Construction Automation", Feb., 1989, p. 78-81

system will cut by 30% the number of man-hours required to complete a 20-story building now under construction in Nagoya, Japan.[7] The Mighty Shackle Ace, developed by Shimizu Corp., is a simple radio-controlled device that releases a crane's lifting cables from a steel beam being placed in a building's framework. The Mighty Shackle Ace not only eliminates the risk to humans who would otherwise have to unhook cables high in the air, but also speeds up the framing process.[8] Studies of other actual sites using automation lead Demsetz[9] and Everett[10] to believe that construction automation could improve the quality of work done because of consistency of output over long periods of time and efficiency of automated inspection. Such a change in inspection would decrease delays caused by a shortage of inspectors; general automation could reduce the duration of construction by promoting increased productivity. Therefore, in the US, Japan, and Taiwan, the construction industry could benefit from wider use of automation as the manufacturing industry has done.

However, the investment in construction automation usually is tremendous and the duration of benefit return is also long. Therefore, those who develop construction automation must determine how to reduce the risk of investment in CA, identify the potential techniques for automation and search for the major constraints.

1.3 RESEARCH OBJECTIVES

This thesis has four objectives. The first is to provide a comprehensive review of the field of construction automation, covering the constraints and the accomplishments

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[7] ENR, "Building-by-numbers in Japan", March 1993, P.22-24

[8] Moore, Walt, "Construction Robotics: Removing Danger and Drudgery from Your Jobs", Construction Equipment, July 1991, P.26-34

[9] Demsetz, Laura A., "Automated and Robotics for Construction", The Construction Specifier, Jan. 1990, P. 84-93

10 Everett, John A., "Construction Automation: Basic Task Selection and Development of the CRANIUM", June 1991, P. 20-55

when developing construction automation in the US, Japan, and Taiwan, and the methodologies that have been carried out to identify appropriate techniques for automation. The second objective arising from the results of the comparison of those various methodologies is to design a new methodology of feasibility analysis for construction automation. The third objective is to compare the current constraints when developing construction automation in these three countries, and to identify proper techniques for automation based on the results of questionnaires. The fourth objective is to provide recommendations to the construction industries and predict the future development of construction automation in the US, Japan, and Taiwan.

1.4 RESEARCH APPROACH

In order to comprehend the background of the construction industry, to analyze the constraints when developing construction automation, and to identify potential techniques for automation, a questionnaire and a new methodology have been designed. The questionnaires were sent to the contractors in the US, Japan, and Taiwan. Based on the results of this survey, the major constraints and the potential techniques for automation in these three countries could be compared.

1.5 THESIS ORGANIZATION

Chapter 2 presents the background information for the research described in the remainder of the thesis. The review covers the introduction of construction automation(CA), the special features of CA, and the current constraints and accomplishments of CA in the three countries. The situation of each country's construction industry and the role of government in promoting CA is also discussed.

Chapter 3 suggests a new methodology for identifying potential techniques for automation. Several current methodologies are reviewed and compared. Based on the results of this review, the method of collecting information, the matrix analysis and the factors for automation in construction techniques are selected.

Chapter 4 presents the design of the questionnaire and the results of the survey. The analyses of the results are also described.

Chapter 5 Summarizes the main issues dicussed in the thesis, and conclude the analyses of the survey results.

1.6 CONCLUSIONS

The construction industry has faced several challenges. In order to conquer these, automation which has proven to be successful in the manufacturing industry will be a proper method. In order to reduce the risk of the investment in developing construction automation, the appropriate techniques for automation and the major constraints should be identified. Therefore, this research contains both major constraints when developing automated equipment and systems and a modern method for choosing appropriate tasks or techniques for automation. However, because of the enormous investment in R&D for CA, the development of CA needs to be analyzed separately and cautiously based on the different situations of different countries. In this research, the US, Japan, and Taiwan have been selected for comparison in the development of CA.

CHAPTER 2

BASIC CONSTRAINTS AND CURRENT ACCOMPLISHMENTS OF CONSTRUCTION AUTOMATION

Construction automation has been researched for more than one decade. However, the construction industry has been slow to adapt automation technology for the particular nature of the construction industry. Therefore, to realize the special features of construction industry, and to explore the major constraints have been primary works for improving the development of CA. This chapter emphasizes the basic constraints and the construction automation in the US, Japan and Taiwan.

2.1 DEFINITION OF CONSTRUCTION AUTOMATION

Tucker[11] defined Construction automation as "the work to increase the contribution of machines or tools while decreasing the human input". Ben O. Uwakweh[12] defined construction automation as "the technology concerned with the application of electronic,

[11] Tucker, R. "High Payoff Areas for Automation Applications", the 5th ISARC, June, 1988, P. 9-16
[12] Uwakweh, Ben O., "a framework for the management of construction robotics and automation" 7th ISARC ,P. 556

mechanical and computer-based systems to operate and control construction production." Yuan-e Then[13] defined construction automation as "under the requirement of the construction environment, the work to improve equipment in order to reduce labor, reduce duration, increase productivity, improve the working environment of labor and decrease the injure of labor during construction process".

In this research "Construction Automation" is defined as "the work using construction techniques including equipment to operate and control construction production in order to reduce labor, reduce duration , increase productivity, improve the working environment of labour and decrease the injury of labour during construction process".

2.2 BENEFITS OF CONSTRUCTION AUTOMATION

The benefits from construction automation are different from those from manufacturing, because of the special features of construction industry. Table 2.1 shows the difference between manufacturing and construction industry. The major benefits from construction automation could be derived from the following primary sources:

Manufacturing	Construction
the specification of manufacturing items are simple and consistent	the specification of construction items are various
the process and the supply of material are comparatively successive	each project needs distinctive features
all tasks performed at a permanent location	work dispersed among many temporary locations
workstations are comparatively stable and less affected by environment	rugged and harsh work environment and easily affected by weather
unified decision-making authority for design, production, and marketing	authority divided among sponsor, designers, local government, contractor, and subcontractors
high degree of standardization	small extent of standardization

Table 2.1 Main Features of Construction Versus Manufacturing Industries[14]

[13] Then, Yuan-E, "Investigation and Analysis on Automation of Construction Techniques and Equipments" Jun., 1992, p.1-25
[14] Warszawski, A., "Industrialization and Robotics in Building" P. 7-17

2.2.1. Reducing Labor Requirements

The construction is a very labor intensive industry. However, the cyclical nature of the industry makes it difficult to retain a sufficient pool of skilled workers to support construction as compared to the service and manufacturing sectors. Therefore, reducing labor requirement has become one of the most important works in the construction industry. But, can automation reduce labor requirement? Skibniewski has proven that the employment of automated machines such as Form Cleaning Robots would reduce labor requirement.[15] Another example to prove that automation can reduce labor requirement of construction is Shimizu's Ceiling Panel Positioning Robot, a mobile device that lifts, positions and holds heavy ceiling panels in place, while a worker attaches the panels. Compared to conventional installation methods, Shimizu says, the device eliminates the need for scaffolding, reduces the risk of injury, and increase work efficiency by 50 percent.[16]

2.2.2. Safety Improvements

Construction remains one of the most hazardous ways to earn a living. Activities such as fireproof spraying, can be detrimental to workers' health in the long run because of the turbid air full of rock wool which is scattered and cementitious liquid which is splashed. Others like foundation work and working at heights can expose workers to serious accidents. While statistics may capture the frequency and severity of construction accidents, the costs in terms of human misery cannot be quantified. Therefore, the safety and health improvements have been a very important issue for construction industry. These

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[15] Skibniewski, M. J., "Robotics in Civil Engineering" P. 4-52
[16] Moore, Walt, "removing Danger and Drudgery from Your Jobs", Construction Equipment, July 1991, P. 26-34

are also the potential tasks for construction automation, because automated machines could limit the need for people to work in hazardous environments. The application of robots could also expand construction work into environments in which human performance would be limited by external factors such as radioactive or chemically contaminated work sites. Meanwhile, the improvement in construction safety could also make the industry more attractive to a shrinking labor supply.

2.2.3. Quality Improvement

As the standard of living rises, there is greater demand placed on the construction industry to delivery quality buildings and infrastructure, but a shortage of skilled labor would also make it difficult to maintain construction quality. Therefore, automation become more important because it could not only reduce labor requirement but also help maintain the accuracy in production which will consequently improve the quality standard.

2.2.4. Increasing Productivity

In any work or process including construction, there will be activities that are tedious and repetitive. Productivity would improve tremendously if ways can be found to automate these activities on-site or if applicable, in off site factories.[17] Automation, if carefully integrated with other activities, would enable a more streamlined design and construction process resulting in speedier completion and higher productivity.

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[17] Khoon, Quak SER, "Developing a National Automation Masterplan for th construction Industry", the 5th ISARC, June 1990, P. 471-480

2.3 BASIC CONSTRAINTS WHEN DEVELOPING CONSTRUCTION AUTOMATION

Due to the benefits of the construction automation, the construction industry has been trying to adapt automated techniques, including robotics, since the early 1980's. Meanwhile, it has been reported, in the manufacturing industry, that successfully applied automated technology can improve productivity by 20% to 30%.[18] However, because of several constraints when developing and adapting construction automation, the construction industry has been slow to adapt automated technology. The basic constraints to develop and adapt construction automation are described in the following areas.

1. Lack of Money

The investment to develop construction automation is extremely large. Therefore, only when the future market of CA is clear and potential or the cooperation remains large capital, most contractors and manufacturers would not like to invest in developing construction automation. Therefore, money shortage would make it difficult to develop CA.

2. Difficulty in Finding Technical Employees

The success of automation heavily relies on the cooperation of people with appropriate talents. However, due to the unclear direction of the future development of CA, the related training dose not consistently increase. Therefor, The appropriate talents, including the idea creators, technology users, plan supervisors, and information suppliers, also not consistently increase. Therefore, due to the increasing need of CA, to find such technical employees has become more difficult.

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[18] The Business Roundtable, "More Construction for the Money", Summary Report of the Construction Industry Cost Effectiveness Project, 1983

3. Lack of Insurance

When adapting and developing CA, because there are many uncertainties and the investment is also large, the insurance availability of investment is relatively important. Also, because the injuries rate of research subjects as employees is higher than those for clerical office employees,[19] there is a need for the research injury insurance. Meanwhile, the automated equipment is a product, so it needs the insurance of product liability to insure damage caused by equipment. By these different kinds of insurance, the risk of development of CA would be reduced. On the other hand, "lack of insurance" would be a constraint when developing CA.

4. Rejection by Labor

One of the benefits of CA is reducing labor requirement. Therefore, the labor, who fears that automation will result in a decrease in employment opportunities, a deskilling of remaining jobs, and a decline in wages, usually oppose construction automation.

5. Difficulty in Training

Due to the complicated manipulation of some automated machines, the training usually needs longer time and the laborers sometimes are reluctant to take the training. For example, the use of computer for schedule could shorten the duration of producing schedule diagrams such as bar chart or logical diagram, but it also needs to train the scheduler or the superintendent how to use computer. However, usually the superintendents, who draw the schedule diagram based on the daily report from the construction site, already know how to draw the diagrams manually, and some of them do not know how to use the computer. Therefore, they usually are not willing to use computer, and this makes the adaptation of CA difficult.

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[19] Present's Commission for the study of Ethical Problems in Medicine and Biomedical and Behavioral Research, "Compensating for Research Injuries", Vol. one: report, P. 124

6. Risk of Unstable Future Construction Market

Due to the special features of the construction industry such as minimal standardization and frequent reconfiguration of the operation, sometimes one automated machine could not be used for next similar project. For example, the contractor would use tunneling shields for tunnel construction, but if another tunnel project the contractor has access to is designed to use bigger inner diameter tunnel shield machine, the investment in the original shield machine would be worthless for this similar project. Also, the opportunities of having the similar projects in the future is unclear. Therefore, there is a risk of whether the automated machine could be reused for the contractor's future projects. Due to the unsure future market, many contractors and manufacturers are reluctant to invest in developing CA.

7. Lack of Appropriate Contract Provisions

The purposes of developing CA for contractors are increasing productivity and improving worker safety, but because the clients think that increasing productivity is the responsibility of contractors, they usually do not provide any award to the contractors for using automated techniques or equipment. Therefore, this situation would make the willingness of clients to assist developing CA low.

8. Lack of Experience in Cooperating with International Contractor

In the process of developing CA, many new technologies, which might be developed by foreign companies, are needed. Also, the investment of CA is large. Therefore, under the cooperation with international contractors, the risk of developing CA would be reduced. This reason makes it important to have experience in cooperation with international contractors for CA.

9. Lack of Access to Automated Equipment Supplier

Not all contractors have the ability to develop CA. Therefore, the access to automated equipment suppliers is relatively important in adapting CA. Because the automated equipment might be developed by foreign companies. if the information is not efficient, the contractor might do not know the existence of that automated equipment and of course do not adapt it. For that reason, lack of access to automated equipment suppliers would be a constraint.

10. Lack of Coordination in Design Plan

Usually the construction methods are already designated in the specification. Therefore, if the automated technique has not been standardized yet and designated in the specification, it still could not be used even though it could increase productivity. Therefore, in design plan , including selecting construction methods for specification, the use of automated techniques should already be designated. Lack of coordination in design plan would cause the difficulty in adapting CA.

11. Lack of Turn-Key Project

If the project is a turn-key project, the design engineers and construction engineers could coordinate easily, and consider construction method and equipment together in the planning phase. Under that situation, the adaptation of construction automation would be easier. Similarly, lack of turn-key projects would make the contractors reluctant to adapt CA.

12. Lack of Support from Government

Because the large investment in developing CA is tremendous, if the government funding is sufficient, and the government provides some reward policies for applying automation such as investment tax credit, import tax reduction, and better loan, the risk of the development of CA would be comparatively reduced. Therefore, insufficient support from government would increase the risk for contractors and be a constraint in developing CA.

13. Restrictions in Laws and Policies of Government

If the laws contain some unreasonable restrictions, it would slow the development of CA. For example, the 359th rule of the regulation of construction technology in Taiwan has limit the minimum duration of removing form panel, based on that rule, the import of suspended form technique and high strength concrete has been delayed.

14. Project Too Small to Apply Construction Automation

Only when the projects are composed of many of the same activities, does the application of automated equipment have valuable based on a economic view point. Figure 2.1 shows the economies of scale of automated technique and traditional technique. Therefore, if the projects the contractor have are smaller than the break point, usually the contractors will not attempt to develop and adapt CA.

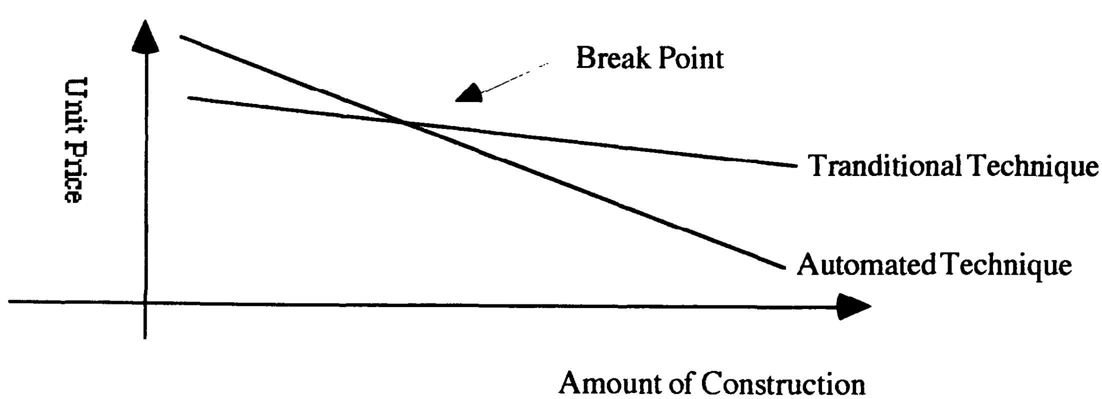

Figure 2.1 Economies of Scale

15. Designers Discourage Construction Automation

The designer is the person to allow contractor apply CA. However, sometimes the designers are very conservative and do not put any use of automated technique or equipment in design because the uncertainties of new technology usually are more than traditional method. Therefore, it would hamper the adaptation of CA.

16. Recession of the Whole Industry

Due to recession, the net profit and net sale of the contractors would decrease, and the investment in R&D would also become less because the contractors usually keep the ratio of (R&D / net sale) stable. Therefore, the recession is a constraint for developing CA.

2.4 CONSTRUCTION AUTOMATION IN THE US

2.4.1 Construction Industry in the US

Construction is a very important part of the US's economy. The share of the GNP accounted for by construction, totals 466 millions US$ in 1993,[20] and is around 10%. Employment in the construction industry, 4.642 million people in 1993[21] , is 15% of the total national employment.

Since the 1960s, the construction productivity in the United State has been decreasing 1% to 2% every year. It is estimated to have decreased by 20% over the past twenty years, a period in which other industries have experienced productivity increases due to their use of ever-increasing sophisticated technologies. Meanwhile, a potential labor shortage, caused by demographic changes and an aging construction work force, has also

[20] Construction Review, "New construction Put in Place in the US", summer 1994, P.1
[21] the US Bureau of the Labor Statistics, 1994, US Dept. of Labor

begun to be of concern to the construction industry. In addition, according to the US Department of Labor's Bureau of Labor Statistics, 565 construction workers were killed in 1993.[22] The construction industry accounted for 9% of all fatalities. Therefore, worker safety is also an important issue and needs to be improved. By facing these challenges, the government, the construction industry and the academia have all tried to solve these problems by automation, especially computerization. Therefore, integrated database, artificial intelligence, construction robots, 3D computer-aided-design, and construction management technology have also been the main research projects of CA in the US.

2.4.2 Role of Government

The US government supports a few important construction research projects. The National Science Foundation (NSF) has been a source of support for university-based research activities.[23] Through the support of the NSF, the Center for Advanced Technology for Large Structural Systems (ATLSS) has been established at Lehigh University. Through the Army Research Office (ARO), a Program for Advanced Construction Technology (PACT) was established at MIT.[24]

The Construction Productivity Advancement Research (CPAR) is a cost shared partnership between the U.S. Army Corps of Engineers and the U.S. construction industry to facilitate R&D of advanced technology. The National Institute of Standards and Technology (NIST) Center for Building Technology is conducting applicable research on a diverse range of topics. Of particular importance is the work on CAD database exchange

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[22] the US Bureau of the Labor Statistics, "Occupational Injuries and Illnesses in the US by Industry", 1993, US Dept. of Labor

[23] Demsetz, Laura A., "Automated and Robotics for Construction", THE CONSTRUCTION SPECIFIER, Jan. 1990, p84-93

[24] Everett, John G., "Construction Automation: Basic Task Selection and Development of the CRANIUM", June 1991, P. 16

standards such as Initial Graphics Exchange Specification (IGES), the Product Data Exchange Specification (PDES), and the dynamically stabilized platform crane.

The federal government can play a significant role in the following ways:[25]

1. Support and expand construction-related research at universities.

2. Collaborate with industry and academia to set data modeling and exchange standards.

3. Support more design and construction work for government agencies in order to encourage integration.

4. Increase the cooperation between government organizations, universities, and private industry for shared research programs

5. Encourage the demonstration of new technologies and new contracting methods.

2.4.3 Current Research on Construction Automation in the US

A number of robotics prototypes and working systems have been developed for application which are potentially transferable to the construction industry. These include areas of building construction, heavy construction, tunneling, foundation construction, concrete construction. nuclear/hazardous construction, steel-structure assembly construction, rock-job construction, and piping construction. However, because many prototypes designed to date usually are developed to mimic to a considerable extent the work of humans in unstructured jobsite environments, there is a need to restructure the jobsite environment to meet the capabilities of relatively unsophisticated, and thus frequently easier to build and more cost effective, construction robotics. As a result, the application of the early prototypical systems frequently proved very difficult or prohibitive due to a high cost. On the other hand, the positive side of the approach was valuable experience gained in such areas as sophisticated robot control systems, sensory data

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[25] Demsetz, Laura A., "Automated and Robotics for Construction", THE CONSTRUCTION SPECIFIER, Jan. 1990, p84-93

processing, artificial intelligence concepts, and machine learning. Significant advances have been made in modeling, and data integration techniques.[26] Therefore, software research and development exceeds hardware design and development in American CA activities. A few current research projects are listed below.

AIBS (ATLSS Integrated Building System) program was developed to coordinate ongoing research projects in automated construction and connections systems in Lehigh University The objective of this program is to design, fabricate, erect, and evaluate cost-effective building system with a focus on providing a computer integrated approach to these activities. ATLSS connections are being developed with enhanced fabrication and erection characteristics.[27]

The Construction Automation & Robotics Laboratory (CARL) at North Carolina State University has been involved in the design, delivery, and placement of steel reinforcement bars. A component of this research deals with the development of a computer-controlled bender with understanding of the behavior of the rebar and developing a model for controlling the operation in order to achieve consistently accurate bent bars.[28]

The United States Air Force is undertaking a research and development effort to develop robotic construction/repair equipment to execute peacetime range clearance as well as post-attack Explosive Ordnance Disposal (EOD) and operate surface repair and recovery during wartime. This development effort involves several technologies: teleoperation, telerobotics, robotic vehicle communications, automated damage assessment, vehicle navigation, mission/vehicle task control architecture and associated computing

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[26] Skibniewski, Mirostaw J., "Current Status of Construction Automation and Robotics in the US", the 9th ISARC, p. 17-24

[27] Viscomi and Lu, "Automated Construction in the ATLSS Integrated Building Systems", the 10th ISARC, May 1993, P. 9-16

[28] Dunston and Bernold, "Intelligent Control for Robotic Rebar Bending", the 10th ISARC, p. 101-117

environment. The ultimate goal is the fielding of a robotic vehicle capable of operating at the level of supervised autonomy.[29]

University of Texas at Austin has been involved in research on site layout of construction temporary facilities (TF) using enhanced-Geographic Information System (GIS). TF is an important preplanning task that can either enhance or adversely affect construction productivity. An efficient TF layout can significantly reduce construction conflicts and improve project efficiency. In this research, Acrostic, developed to assist the project manager in identifying suitable areas to locate TFs, is comprised of a GIS integrated with a database management system (DBMS).[30]

The University of Michigan, Ann Arbor has been involved in research on space scheduling for construction progress planning and control. A Moveplan, used in this research, is a model for dynamic layout planning and is described to illustrate the overall significance of space scheduling to construction progress planning. The model does not require a powerful workstation, but runs on a laptop computer that could easily be taken out into the field.[31]

A number of relevant automated prototypes have been designed and built in the US. Table 2.2 includes a partial listing of some of the automation accomplishments developed to date.

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[29] Nease and Alexander, "Air Force Construction Automation/Robotics", the 10th ISARC, May 1993, P.341-354

[30] Cheng and O'Connor, "Site Layout of Construction Temporary Facilities Using Enhanced-GIS", the 10th ISARC, P. 399-406

[31] Tommelein and Zouein, "Space Scheduling for Construction Progress Planning and Control", the 10th ISARC, may 1993, P. 415-422

Building Construction	
Automated equipment / technique	**Development Organization**
precasted concrete system	Leo A Daly Co.. Honolulu
CORTINA wall panel assembling system	Leo A Daly Co.. Honolulu
building formwork system	Turner International inc.
automated paint sprayer for storage tank	Univ. of Texas

Heavy Construction & Tunneling	
Automated equipment / technique	**Development Organization**
TORCE drilling machine	Deere, Miller Formless
REX drilling machine	Carnegie-Mellon Univ.
soil sampler robot	Iowa State Univ.
John Deere Excavator, model 690c	John Deere, Inc.
force-cognitive excavation	Intec Controls Corp. Carnegie-Mellon Univ.
robotic pavement crack sealing system	Univ. of Texas
laser-aided grading system	GradewayConstruction Co. & Agtec Development Co.
micro-tunneling machine	American Augers
NavLab	Carnegie-Mellon Univ.

Foundation Construction	
Automated equipment / technique	**Development Organization**
automated foundation-operating machine	Univ. of Texas. Grove, Dupont
welding quality control system	CERL
underwater screw-arranging & fastening equipment	Constructors Engineering

Concrete Construction	
Automated equipment / technique	**Development Organization**
automated slip form machine	Miller Formless
automated rebar-welding machine	EVG
automated rebar-assembling machine	MIT
automated rebar-bending assembling machine	EVG, North Carolina state Univ.
bulk cement unloading system	Miller Formless
concrete vibrating machine	Pentek Inc.
runway rapid-repairing machine	Deere, Westinghouse Univ. of Florida
road crack-filling machine	Carnegie-Mellon Univ.
robotic construction /repair equipment for range clearance/EOD	U. S. Air Force

Nuclear / Hazardous Construction	
Automated equipment / technique	**Development Organization**
reactor vessel dismantling system	Bechtel inc.
automated inspection of earthworks system	ConSolve inc.
remote reconnaissance vehicle	Carnegie-Mellon Univ.

Steel-Structure Assembly Construction	
Automated equipment / technique	**Development Organization**
automated structure erection system	Lehigh Univ.
automated arrangement & bean-joining system	Lehigh Univ.
automatic welder	MIT
interior wall placing machine	MIT

Table 2.2 Current Accomplishments of Construction Automation in the US

Stone-Job Construction	
Automated equipment / technique	**Development Organization**
Wallbot, Blockbot, shear stud welder	MIT
rock eradicating machine	Univ. of Maryland

Piping Construction	
Automated equipment / technique	**Development Organization**
B.B.T.	Constructors Engineering
semi-automated piping erection system	Univ. of Texas
ergonomic control system	Univ. of Texas
automated pipe bending system	Univ. of Texas
pipe installation motion planner	Stanford Univ.

Construction Management System / Control System for Robots	
Automated System	**Development Organization**
management of spatial information using geographical information systems(GIS)	Univ. of Texas
artificial reality in robotics and A/E/C firms	Georgia Institute of Technology
CREMS	Purdue Univ.
activity-level space scheduling	Univ. of Michigan
time-dependent evolution of work packages	Univ. of California
planning for automatic excavator operations	Purdue Univ.
task and motion planning technique	Purdue Univ.
construction information system	Univ. of Wisconsin
heuristic application specific path planner	Univ. of Texas
control system for CIC	Univ. of Maryland
ATLSS integrated building system	Lehigh Univ.
intelligent control for robotic rebar bending	North Carolina State Univ.
enhanced GIS for TF layout	Univ. of Texas
space scheduling	Univ. of Michigan
integration in design and simulation	Stone & Webster Engineering Corp.

Table 2.2 Current Accomplishments of Construction Automation in the US (cont'd)

source from: "6th ISARC"; "7th ISARC"; "9th ISARC"; "10th ISARC"; Masayuki Nozaki, "Technology of Architecture: construction"; Katsuji Komijama & Hideaki Kanaya,"The Current Status and Issue of Japanese Automatic Mechanization and Technology Development", Construction Prices; BRI, Ministry of the Interior, "The Report of Construction Automation Investigation Group".

2.5 CONSTRUCTION AUTOMATION IN JAPAN

2.5.1 Construction Industry in Japan

The Japanese domestic construction industry is huge. It is the largest of any nation at an annual volume of approximately $500 billion.[32] The Japanese construction industry represents approximately 18 percent of the gross national product, about twice the percentage for the US construction industry. However the construction industry of Japan has also faced several problems and changes. The labor shortage of skilled construction workers has continued to increase since 1985, and had reached 4.5% by 1990. At the same time, Japan's work force is aging, with up to 30.5% of the total labor force in construction being over 50 years old.[33] Mechanization and systems engineering are essential elements for the nation's response to the need for labor-saving construction methods. In addition and with respect to safety, the construction industry accounted about 40% of all fatalities in 1990.[34]

In order to solve these challenges, the Japanese construction industry has been involved in research on robotics and semiautomatic construction equipment. The objectives are first to increase the productivity of craftsmen by automation;[35] second to improve the safety of workers; and finally to be able to compete with other companies, because what is accomplished in technology research is a selling point to not only new clients but also to long-term clients.

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[32] Tucker, R. L., "Japanese Construction Industry", Automation in Construction 1 (1992), P. 27-34
[33] Ministry of Construction, "Labor force", White Paper on Construction 1991, P. 84
[34] Ministry of Construction, "Labor force", White Paper on Construction 1991, P. 100
[35] Nielsen, R.W., "Construction Field Operations and Automated Equipment", Automation in Construction, 1992, P. 35-46

2.5.2. Role of Japanese Government

The mechanization of the Japanese construction industry began in 1950s.[36] However, even though the accomplishment in the development of construction techniques and the research of construction robotics is obviously great, the prototype automated equipment and robotics has not completely found its way into the field. Reasons such as cost and inadequate productivity have been given for the lack of success. By facing the failure, the Japanese construction industry and government has worked together to save the situation.

The Japanese construction industry has a great amount of public and private interaction. Various governmental organizations, such as the Ministry of Construction (MOC) and the Ministry of International Trade and Industry(MITI), provide assistance to the Japanese industry. The Building Research Institute (BRI) and the Public Works Research Institute(PWRI),[37] which are subsidiary organizations of MOC, collaborate with industry on research.

Since 1978, Japan has been conducting research on importing robotics into construction industry. The Japanese Industrious Robotics Association (JIRA) established the Robotics Research and Development Committee(RRDC), which is developing construction automation. This committee is headed by Professor Yukio Hasegawa of Waseda University. Eleven companies are participating in the committee's work, including the top contractors, construction equipment manufacturers, electronics firms and a shipbuilding company who are working together on the WASEDA CONSTRUCTION ROBOT PROJECT (WASCOR). While industry representatives do most of the detailed

[36] Building Research Institute, "Investigation of Current Situation of Construction Automation in Japan", Mar. 1991, P. 1-30
[37] Tucker, R. L., "Japanese Construction Industry", Automation in Construction 1 (1992), P. 27-34

development work, the university staff provides direction and expertise on difficult research problems.

Most of the general contractors who are participating in WASCOR also joined the RRDC. These members, as the center of the construction automation and robots project, are also working on their own development projects for automation. In 1982,[38] there already were construction robots operating on the construction site. A much more extensive campaign for design and construction automation is currently being waged by the BRI in one of its typical joint ventures with the construction industry. Each year, the BRI announces a series of research initiatives and invites construction industry firms to participate. The agency often also invites universities to participate in the research. In 1990 the BRI included as one of its research initiatives, a program for "Advanced Construction Technology R&D." and invited the construction industry's participation. By 1991, twenty construction firms had agreed to participate and allocated R&D staff and funds.

The Ministry Of Construction's primary administration direction is to improve construction productivity and to train more technical people in order to promote the construction industry. This is intended to strengthen the operating ability of the construction industry, promote the efficiency of construction such as robotization and prefabrication, and develop a network for construction industry information. At the same time, MOC also implements programs to reduce labor shortage, improve safety, and appeal to young people to seek employment in the construction industry.

The Japanese government organized several committees to promote many projects related to construction automation and robotics. Meanwhile, many building associations, building technology centers, and construction equipment associations also worked on the

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[38] Webster, Anthony C., "Technological Advance in Japanese Building Design and Construction", 1994, P. 83-87

integration of robotization. atomization and energy saving through various committee activities. Japan has been the pioneer[39] for developing the construction robot , and is also in the world leader for the result of importing robots to the job site.

2.5.3 Current Research on Construction Automation in Japan

In Japan, construction automation and robots are mainly developed by building corporations and manufacturers. Therefore, there are more robots operated for building construction than those operated for civil construction. The research projects in those corporations are all very confidential, therefore, it is normal that several corporations developed various style and level of automation equipment for the same construction activity. Most of the big contractors have developed many robots and automated equipment for both building and civil construction. The following areas are some examples of current research projects.

Takenaka Corporation has applied a new construction method, ROOF PUSHUP CONSTRUCTION METHOD, to a real construction project and obtained positive results in shorter construction time and manpower savings. This method can automate, robotize, and industrialize various aspects and phases of construction in all weather conditions.[40]

Shimizu Corporation has been involved in research on a lift up intelligent control system. This system is different from conventional lift-up construction method in the following respects. (1) It is not necessary, as it is in conventional lift-up systems, to install jacks on column capitals. and the system in capable of self-climbing with the built-in columns. (2) In floor-size and other large-size structures, the distributed load varies

[39] Building Research Institute. "Investigation of Current Situation of Construction Automation in Japan", Mar. 1991, P. 60-90
[40] Morita, Muro, Kanaiwa and Nishimura, "Study on Simulation for ROOF PUSHUP CONSTRUCTION METHOD", the 10th ISARC. may 1993, P. 1-8

depending on the thickness; and the balance of the structure is disrupted if the same lifting power is applied to each lifting point. Use of a control device for the lift-up made it possible to do synchronized lifting in accordance with the load balance.[41]

Fujita corporation has been involved in research on a system for vertically sliding and installing exterior curtain wall of a building. This system, referred to as a "shuttle system, " has been developed to enable the vertical sliding and subsequent installation of panels on the exterior walls of a building. Various sensors are provided to enable the panel unit to be installed accurately both in horizontal and vertical directions.[42]

Miyazaki University has been involved in research on a propeller type wall-climbing robot for inspection use. This robot has propellers, and their thrust forces are inclined a little toward the wall to make use of the frictional force between the wheels and the wall surface, as well as to support the robot itself.[43]

Kajima Corporation developed an exterior wall painting robot for the purpose of automating this painting operation. The robot is mounted on equipment which permits it to move up and down, left and right along the exterior walls of a building. It is computer controlled and is activated simply by the operator pressing a switch on the control panel located on the ground.[44]

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[41] Tezuka and Takada. "A Lift Up Intelligent Control System", the 10th ISARC, may 1993, P. 17-22
[42] Iwamoto, Nakagawa, and Oda, " A System of Vertically Sliding and Installing Exterior Curtain Walls of a Building", the 10th ISARC, may 1993, P. 77-84
[43] Nishi and Miyagi, "Propeller Type Wall-Climbing Robot for Inspection Use", the 10th ISARC, May 1993, P. 189-196
[44] Tobitakyu, "Development of an Exterior Wall Painting Robot Capable of Painting Walls with Indentation and Protrusions", the 10th ISARC, May 1993, P. 285-292

A number of relevant automated prototypes have been designed and built in Japan. Table 2.3 includes a partial listing of some of the automation accomplishments developed to date.

Building Construction		
project classification	automated technique / equipment	research organization
Steel Frame Structure	steel frame erecting robot	Shimizu
	automated hook release system	Shimizu, Obayashi
	automated position controlling system	Taisei
	steel frame welding robot	Fujita
	STUD welding robot	Kajima
	steel column welding robot	Obayashi, Mitsubishi, Shimizu, Hitachi
	automated steel column welding robot	Shimizu
	fireproof spraying robot	Shimizu, Fujita, Kobe
	automated operating system for crane	Konoike, Hazama
	inter sensing survey system for crane	Kajima, Konoike, Shimizu, Sumitomo, Mitsui, Sato, Takenaka
	remote control machine of crane hanger	Obayashi, Nishimatsu, Shimizu
	survey controlling system for tower crane	
Reinforced Bar	automated rebar assembling crane	Takenaka, Shimizu
	rebar tightening machine	Taisei
	beam with reinforcement assembling machine	Obayashi, Taisei
	rebar placing robot	Kajima
	automated rebar processing machine	Shimizu
	automated rebar reinforcing system	Shimizu
Concrete Construction	movable concrete placing machine	Tokyu
	fixed concrete placing machine	Mitsubishi
	tower crane concrete placing machine	Obayashi, Takenaka, Konoike, Toda
	automated concrete floor paving machine	Shimizu, Takenaka, Fujita
	remote controlled concrete floor finishing machine	Fujiko, Takenaka, Shimizu, Kajima, Obayashi
	floor cleaning machine	Shimizu
	supervising system on crane	Kajima, Konoike, Sato, Shimizu, Sumitomo, Taisei, Takenaka-Fujita, Mitsui
	automated operating system on crane	Konoike, Hazama
	automatic screeding machine for concrete placing work	Takenaka
	automated wall and presaving hole cleaning machine	Fujita
	concrete condense crane	Takenaka
	concrete paving machine	Tokyu
	automated concrete mixing machine	Obayashi, Kumagai

Table 2.3 Current Accomplishments of Construction Automation in Japan

Building Construction		
project classification	automated technique / equipment	research organization
Exterior Wall Finishing Work	exterior wall maintenance robot(painting, cleaning)	Kumagai, Shimizu, Taisei, Takenaka, Fujita
	automated exterior precast concrete wall panel construction system	Fujita
	automated exterior precast wall installation machine	Kagima, Komatsu, Fujita
	exterior tile diagnosing machine	Obayashi, Kajima, Taisei, Kumagai, Takenaka, Fujita, Kansai, Mitsubishi
	exterior wall cleaning machine	Shimizu, Obayashi
	automated exterior wall coating removal machine	Takenaka, Kumagai, Nishimatsu, Tokyo Denki Univ.
	semi-automated spray fireproofing system	Takenaka
	wall-climbing robot for inspection	Miyazaki Univ.
	tile placing robot	Hazama, Komatsu
Interior Wall Finishing Work	ceiling installation robot	Shimizu, Tokyu, Kumagai-Gumi
	glass installation robot	JDC
	glazing robot	Asahi
	glazing machine	Chuo
	partition board installation robot	Obayashi, Taisei, Mitsui
	material transport robot	Shimizu, Taisei, Takenaka
	automated elevating operating-platform	Takenaka
	ALC panel installation machine	JDC
	sky hand	Kumagai
	manipulator for building construction	Komatsu, Takenaka
	mite-hand	Komatsu, Kajima
Piping Construction	pipe welding machine	Hitachi
	pipe system diagnosing robot	Obayashi, Taisei, Mitsui
Other Construction	automated graphite elevator	Obayashi
	asbestos pealing machine	Sato
	automated building installation system	Obayashi
	window cleaning robot	Nippon Besom, Mitsubishi
	clean room diagnosing robot	Obayashi, Kumagai, Hitachi Plant, Komatsu, Hazama
	material handling system	Shimizu, Mitsubishi Heavy
	desk/chair arrangement robot	Fujita
	roof pushup construction method	Takenaka, Shimizu

Tunneling Construction		
project classification	automated technique / equipment	research organization
Surveying Construction	observation system for excavation stratum analysis	Konoike, Sumitomo
	computer surveying system for excavation section	Kumagai, Hazama, Shimizu, Zenitaka,
	laser marking system for tunnel excavation section	Taisei, Sato, Toa, Obayashi
	concrete lining inspection system	Mitsui

Table 2.3 Current Accomplishments of Construction Automation in Japan (cont'd)

Tunneling Construction		
project classification	automated technique / equipment	research organization
Excavation Construction	automated operating system for electrometer	Kajima, Nishimatsu
	Robot Jumbo	Obayashi, Kajima, Toyo-Kogyo, Furukawa, Hazama, Kumagai, Mitsui
	automated filling explosive machine	Taisei
	total control system for shotcreting	Toa
	grout system	Taisei
	preventing over-excavation system	Nishimatsu
Lining Construction	concrete spraying robot	Obayashi, Kajima, Taisei, Kumagai, Saga, Tekken, Tokyu, Tobishima, Nishimatsu, Mitsui, Miike
	automated slurry piping connection	Konoike, Aoki
	lining machine with changeable spraying system	Mitsui, Saga, Tekken
	steel rib installation robot	Tokyu
	automated installing and welding water-proofing membrane machine	Sato
	sliding press lining robot	Fujita
	automated NATM segmental ring assembling machine	Kumagai
	automated air-changing ventilator	Obayashi, Tobishima, Mitsui, Miike
Repairing Construction	concrete chipping robot	Tokyo-Electric, Kandenko, Todensekkei, Kumagai-Gumi

Tunneling Shield Construction		
project classification	automated technique / equipment	research organization
Vertical Shaft	automated vertical shaft excavation equipment	Takenaka-Doboku, Mitsui
Excavation Construction	fore prospecting system	Komatsu, Hazama, Tekken, Toda, Hitachi, Mitsui
	automated excavation direction controlling system	Obayashi, Okumura, Shimizu, Kajima, Kumagai, Penta-Ocean, Sato, Konike, Sumitomo, Fujita, Taisei, Takenaka-Doboku, Tekken, Tobishima, Tokyu, Maeda, Nishimatsu, Hazama, Fudo, IHI, Kawasaki, Hitachi
	automated slurry transport pipes machine	Shimizu, Kumagai
	discharged soil measuring device	Mitsubishi
	surveying system	Toyo
	construction management system	Aoki, Obayashi, Hazama, Toda, Mitsubishi

Table 2.3 Current Accomplishments of Construction Automation in Japan (cont'd)

Tunneling Shield Construction		
project classification	automated technique / equipment	research organization
Lining Construction	automated segmental ring assembling machine	Kajima, Shimizu, Taisei, Toda, Kumagai, Komatsu, IHI, Hitachi, Kawasaki-Juko, Hazama, Maeda, NKK
	unmanned prelining machine using PASS method	Fujita
	automatic bolt supply and tightening robot	Nishimatsu, Kawasaki
	automated segmental ring transportation system	Shimizu, Taisei
	automated rebar installing system	Shimizu
Ground Intermediate Connection	automated connection system of mechanism tunneling shield	Shimizu
Propelling Construction	automated propelling system	Okumura, Kubota, Tokyu
	propelling method controlling system	Zenitaka, Fujiko

Dam Construction		
project classification	automated technique / equipment	research organization
Rock Excavation	no explosives rock cutter	Kajima
Foundation Disposal	GROUT PUMP	Toto-Denki, Yamodo- Boring
	automated grouting system	Taisei
Concrete Transporting	auto-adjusted TRANS-FORK	Kajima, Obayashi, Shimizu, Konoike, Tobishima, Maeda, Hazama, Hitachi, Fujita, Nishimatsu
	automated cable crane	Hitachi, Hazama
	cable crane(auto-adjusted main cable)	Nishimatsu
	automated incline conveying facility	Nishimatsu
	automated tower-crane	Tohoku, Hazama
	moveable tower-crane	Shimizu
	inter-continuous belt conveyor	Nishimatsu
	expansion belt conveyor for RCD	Hazama
	LIFT-UP pier	Nishimatsu
Concrete Placement	automated concrete roller	Mitsubishi, Fujita
	automated form panel cleaning machine	Nishimatsu
	automated installing / removing steel form panel system for dam	Obayashi, Hazama, Kajima, Kumagai, Sato, Shimizu, Taisei, Tobishima, JDC, Mitsui, Nishimatsu, Maeda,
	GRIND-CUT machine	Kajima, Taisei, Sato, Tobishima

Table 2.3 Current Accomplishments of Construction Automation in Japan (cont'd)

Pavement Construction		
project classification	automated technique / equipment	research organization
Road Bed	automated road roller	Sakai-Juko, Kajima
	auto-operated deep rammer	Nippon-Hodo
Asphalt Paving Construction	automated asphalt finisher	Kajima road, Mitsubishi, Sumitomo-Kenki, Nippon-Hodo
	auto-bending screed ruler	Kajima-Road
	automated asphalt mixing plant	Taisei-Road
	Road Cutter	Komatsu
	lateral moving form corrier	Kajima-Road
	pavement cooling facility	Kajima-Road, Seikitokyu-Kogyo, Nippon-Hodo
Concrete Paving Construction	movable concrete mixing plant	Seikitokyu-Kogyo, Nippon-Hodo
	automated vertical concrete finisher	Kajima-Road
	automated concrete finisher	Nippon-Hodo, Seikitokyu-Kogyo
	concrete paver	Nippon-Hodo
	thick skeleton paver	Nippon-Hodo
Pavement Re-activating	automated pavement re-activating machine	Taisei-Road
	pavement heater	Kajima-Road
Other	pavement condition inspecting machine	Komatsu
	scattered RI method for concrete quality control system	Mitsui

Earth Work Construction		
project classification	automated technique / equipment	research organization
Earth Excavating Construction	automated wheel loader-dozer	Komatsu, Mitsubishi, Sumitomo, Kawasaki-Juko,
	automated earth excavator	Kubota
	automated dozer	Komatsu
	automated paver	Komatsu
	automated shovel	Komatsu, Mitsubishi, Kobe-Seiko, Sumitomo-Kenki, Hitachi-Kenki, Zenitaka
	auto-operating system of incline unloader	Komatsu, Mitsubishi
	operation controlling system of heavy equipment	Mitsui, Kawasaki-Juko
	earth measuring controlling system	Shimizu, Taisei
	movable belt conveyor	Nippon conveyor
	automated rock cutter	Komatsu
Measuring	automated measuring machine for roller	Mitsui, Fudo, Tokyu

Foundation Construction		
project classification	automated technique / equipment	research organization
Caisson Construction	automated pneumatic caisson system	Kajima, Shiraishi, Mitsui, Daiho, Tokyo-Electric-power
Underground Slurry Wall Construction	excavation controlling system	Obayashi, Shimizu, Taisei, Sumitomo, Hazama
	concrete placing robot	Obayashi
	automated sewage controlling facility	Obayashi
	sedimentation soil treatment machine	Takenaka

Table 2.3 Current Accomplishments of Construction Automation in Japan (cont'd)

Foundation Construction		
project classification	automated technique / equipment	research organization
Piling Construction	automated earth auger	Onoda, Kobe-Seiko, Nippon
	automated roll-up system of auger	Toyo-Unpan
	automated position controlling system of auger	Obayashi, Shiraishi, Konoike, Mitsui
	automated wheel pile driver	Obayashi, shiraishi, Konoike, Mitsui
	automated reinforced cage installing machine	Konoike
Stratum Improvement	remote controlled stratum improving machine	Konoike
	paper drain machine	Toyo, Daito
	mechanical consolidation system	Fudo

Reinforced Concrete Construction		
project classification	automated technique / equipment	research organization
Reinforcement Construction	automated rebar arrangement machine	Kajima
	automated reinforced steel cutting / bending machine	Aoki, Obayashi, Konoike
	unit automated rebar arranging machine	Shimizu, Takenaka
	automated rebar tie and arranging machine	Taisei
Operating-Platform Pattern	automated elevating operating-platform pattern	Kajima, Fujita, Hazama, Sumitomo, Zenitaka, Tobishima
	automated position inspecting system of operating-platform pattern	Shimizu
Concrete Construction	automated concrete pump car	Daiwa, Niigota
	automated grinder for wall surface	Shimizu
	automated concrete surface peeler	Sato
	automated concrete bucket	JDC
	automated concrete mixing device	Obayashi

Underwater Construction		
project classification	automated technique / equipment	research organization
Investigation Surveying	submarine for under-sea investigation	Komatsu
	ocean investigation system	Kajima, Taisei
Dredging Work	automated pump ship	Komatsu, Toyo
	automated grab ship	Mitsubishi, Kobe-Seiko
	under-sea walking dredge robot	Mitsubishi, Dengyosya, Penta-Ocean
Underwater Civil Engineering	underwaterdozer	Konatsu
	underwaterexcavator	Toyo
Underwater Civil Engineering	automated riprap supply type mound leveling machine	Komatsu, Penta-Ocean, Port and Harbor Research Inst.
	riprap roller	Kajima, Toe
UnderwaterTank	automated preassembling system for reinforcement of underground LNG tank	Shimizu, Tokyo Gas
Piling Construction	automated underwater cutter for steel pipe	Sumitomo

Table 2.3 Current Accomplishments of Construction Automation in Japan (Cont'd)

Masonry and Other		
project classification	automated technique / equipment	research organization
Masonry Construction	concrete product installer	Komatsu
	automated masonry machine	Tokyu, Hitachi
Other	bridge-painting robot	Kawasaki
	automated PC steel bar locking system	Sumitomo
	Wire-Cutter	Obayashi
	automated water knife	Kajima, Hazama, Komatsu, Kumagai
	automated steel pipe inspection system	Fujita
	automated snowplow	Nichijo manu. co
Hazardous Construction	dismantling biological shield concrete machine	Shimizu

Table 2.3 Current Accomplishments of Construction Automation in Japan (Cont'd)

source: "6th ISARC"; "7th ISARC"; "9th ISARC"; "10th ISARC"; Masayuki Nozaki, "Technology of Architecture: construction"; Katsuji Komijama & Hideaki Kanaya,"The Current Status and Issue of Japanese Automatic Mechanization and Technology Development", Construction Prices; BRI, Ministry of the Interior, "The Report of Construction Automation Investigation Group"

2.6 CONSTRUCTION AUTOMATION IN TAIWAN

2.6.1 Construction Industry in Taiwan

Apart from a brief peak in the late 1970s, since 1952 Taiwan's construction industry has tended to contribute around 4-5% of GDP (4.6% of 4,710.2 billion NT$ in 1993).[45] Most of the construction corporations in Taiwan, compared to those in USA and Japan, are medium and small in size. Therefore, the promotion of construction equipment and techniques is really relied on for the implementation of major public construction projects in order to reduce the risk of investment of private construction companies.

Since 1973, The Ten, Twelve, and Fourteen National Projects, which included many large construction projects such as the First Super Highway, Taichung Harbor, the Cross-Wise Roads in the North, Middle, and South Part of Taiwan, Railroad Undergroundization, and Chung-Cheng International Airport, were the major impetus to

[45] China Culture Service, Monthly Statistics of the Republic of China, 1994

promote the Taiwan's construction industry. Since then, the construction industry had reached the construction mechanization stage. However, because the change of the society, the environment of construction industry is facing more challenges in the following areas:[46]

1. sever lack of construction labor and technical labor, and the increasing wages for labor.
2. the high requirement for welfare and labor safety protection.
3. the stronger demand for high quality of construction, reduction of construction duration, and higher productivity.

Therefore, simple mechanized construction could no longer satisfy the requirement of the society. The industry needed a stimulation by a gigantic public project for its promotion in order to face the challenge above.

Meanwhile, an upsurge in construction activity is now taking place, promoted by the government's Six-Year National Development Plan (1991-96) which also includes several major national construction projects such as the rapid transit systems for Taipei, Taichung, and Kaohsiung. Other major projects, including a high-speed train system, will also extend beyond the end of the century. The Government will spend about 223.7 billion US$ to implement more than six hundred public investment projects.[47] Because of the urgency of the development plan, the lack of labour, and the requirement for better construction environments. the government began to support construction automation, and to encourage construction corporations and research institutes to develop appropriate automated equipment and techniques in order to promote the whole industry.

2.6.2 Role of Taiwanese Government

[46] Then, Yuan-E, "Investigation and Analysis on Automation of Construction Techniques and Equipments" Jun., 1992, p.30-78
[47] Ministry of Economic affairs "Six-Year National Development Plan of The ROC" Apr., 1994

The Executive Yuan started to implement The Construction Automation Plan in 1991 (1991-2000),[48] and established a construction automation executive group to organize the project's planning, integration and coordination. The Building Research Institution(BRI), Ministry of the Interior is responsible for the plan's implementation, and expects to elevate Taiwan's construction industry under the cooperation of contractors, government, institutions, architects, suppliers, and other related associations. In April 1990, BRI established a research group to explore five subjects: planning design automation, construction management automization, construction equipment atomization, construction material atomization, and intelligent building. Figure 2.2 shows the implementing organization structure for construction automation. The Committion on Public Works, The Executive Yuan also drew up stratagem for implementing construction automation in 1990[49] in the following areas:

1. to establish a structure for implementing atomization.
2. to create atomization environment in order to attract the industry to join.
3. to promote automated techniques to elevate construction quality.
4. to strengthen the training of automation technician for the need of atomization.

In 1992, the Construction And Planning Administration also announced reward method of investment tax credit to encourage construction corporations to purchase automated equipment and techniques. It is obvious that the Taiwan's government has strong ambitions to promote construction automation in Taiwan.

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[48] BRI "The Report of Construction Automization Group, Ministry of the Interior", 1990
[49] Then, Yuan-E, "Investigation and Analysis on Automation of Construction Techniques and Equipments" Jun., 1992, p.30-78

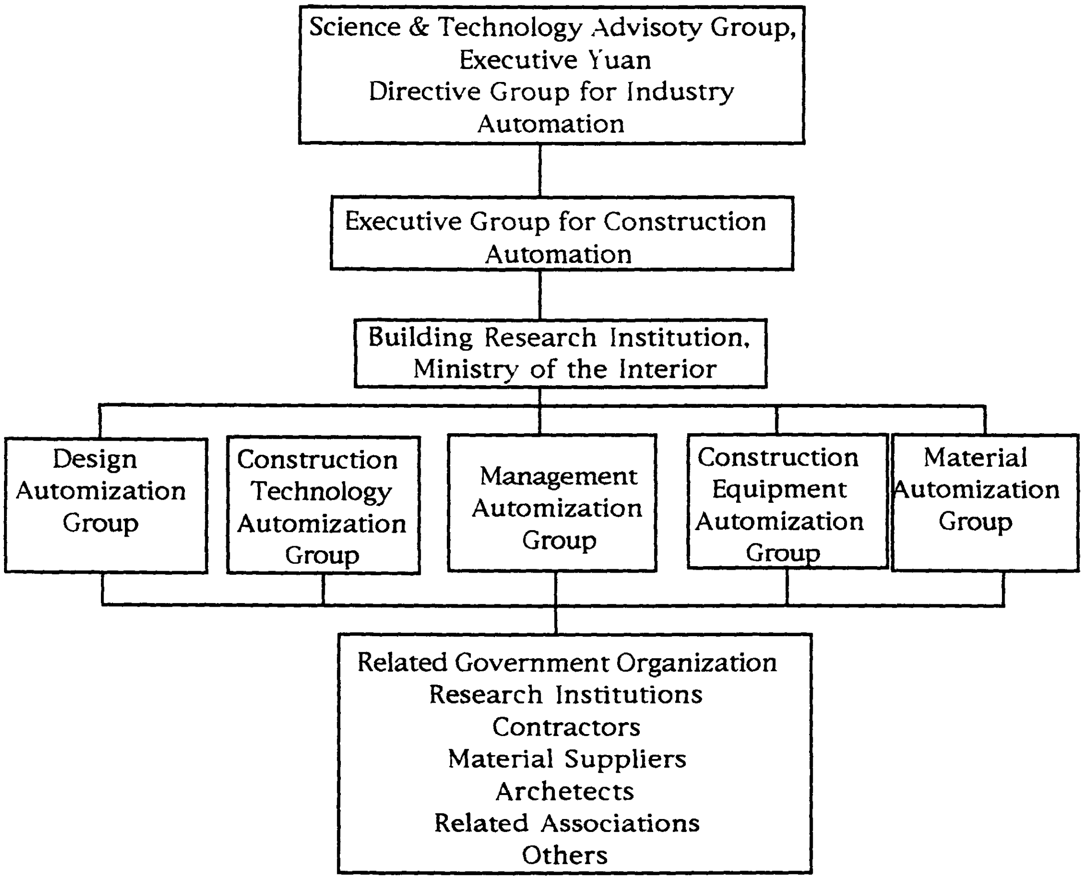

Figure 2.2 Implementing Organization Structure for Construction Automization

2.5.3 Current Research on Construction Automation in Taiwan

Because most of the contractors in Taiwan are small and medium size, most of the research projects related to the construction automation are organized and supported by government. Also, due to the small size of the market for construction automation in Taiwan, most of the research projects are related to the computer integration. Such research includes the computer integrated construction management system by Taiwan Industrial Institute of Technology, the integration of coding principle by Taiwan Industrial Institute of Technology, the expert system for building construction management by Taiwan University and the Management Information System for contractors by Taiwan University.

Table 2.4 shows the current accomplishments of construction automation developed by Taiwanese private organizations.

Automated Equipment / Technique	Research Organization
automated dynamic test pile system	RSEA
automated supervision alarming system	
automated surveying machine for tunnel section	
construction management information system	
movable steel form for tunnel construction	
automated rebar placing machine	China Construction Co.
automated cover panel welding machine	New Asia Construction & Development Co.

Table 2.4 Current Accomplishments of Construction Automation Developed by Taiwanese Private Organizations

2.7 SUMMARY

This chapter placed emphasis on the basic constraints and construction automation in the US, Japan, and Taiwan. Sixteen basic constraints have been selected to be put in the questionnaire for identifying the major constraints in these three countries from the results of this thesis's survey. After reviewing the current accomplishments of CA, the method of classification of CA has also been further analyzed as a matrix form which contains techniques and construction projects. Based on the basic constraints and the method of classification of CA, the survey for identifying major constraints and potential technique for automation could be designed.

CHAPTER 3

THE FEASIBILITY ANALYSIS FOR CONSTRUCTION AUTOMATION

For finding the major constraints which are more serious than other constraints and will be more serious in the future, the current constraints have been reviewed in chapter 2 and used in a survey. In order to identify the potential techniques for automation, several methodologies have been reviewed and compared, then a new methodology needs to be designed. Meanwhile, the categories of major construction projects and techniques which has been concluded in chapter 2 will also be used for the matrix analysis form of the new methodology for identifying appropriate techniques for automation.

This chapter will start with a description of the purpose of the feasibility analysis, then review and compare of current feasibility analysis methodologies, and finally present a new methodology designed by the author .

3.1 THE PURPOSE OF FEASIBILITY ANALYSIS

Construction activities and tasks, which constitute the construction project, are numerous and complicated. Furthermore, the cost and time spent on the development of construction automation for each task or activity are also tremendous. Therefore, in order to efficiently promote construction automation, it is necessary to develop a methodology to analyze the feasibility of automation for construction activities or tasks. The purpose of this feasibility analysis is to identify the automation opportunities in the construction arena. Recently, many different methodologies for feasibility analysis have been developed. The next section will introduce several methodologies and also analyze the advantages and disadvantages of each.

3.2 CURRENT METHODOLOGIES FOR THE IDENTIFICATION OF AUTOMATION OPPORTUNITIES IN CONSTRUCTION

In 1989, Kangari and Halpin[50] evaluated and numerically ranked the major construction production processes, which were carefully selected by experts, based on the analysis of the need, the technological feasibility, and the economic feasibility of automating or robotizing each process. The need-based feasibility is composed of ten subfactors, including labor intensiveness, vanishing skills, require high skills, dexterity and precision, repetitiveness, tedious and boring, critical to productivity, unpleasant and dirty, hazardous to health, and physically hazardous; five subfactors, including material handling, require sensor, control software, control hardware, end effector, constitute the technological feasibility; the economic feasibility is evaluated by three subfactors, including productivity improvement, quality improvement, saving in labor.

In the same year, Koskela, Lempinen and Salo[51] collected needs and ideas for robotization by interviewing experts from the construction industry. From these ideas, seven construction robotics themes, including crane automation, automation of the

[50]Kangari & Halpin, "Potential Robotics Utilization in Construction" Journal of Construction Engineering and Management, Vol. 115, No. 1, Mar, 1989, p.126

[51] Koskela, Lawi, et. al., "The feasibility of Construction Robotics in Finland and Norway" the sixth ISARC, p.80

prefabrication of facade components, robotization in inner works, equipment for materials handling on site. masonry robotics, concreting automation, and measuringment, positioning and navigation techniques in construction, were chosen for further analysis which included identifying functional requirements and conducting a preliminary technical analysis.

Also in 1989, Paul Fazio[52] first prioritized the parameters and overall needs based on the Multiple Binary-Decision Method[53] and on the Analytic Hierarchy Method.[54] He divided the need feasibility into three levels which are composed of eleven factors and collected the information from surveys, C.S.S.T., the agency which regulates safety and security in the workplace, and C.C.Q., the agency to which all hours worked and wages paid must be registered. His automation index model is shown in figure 3.1.

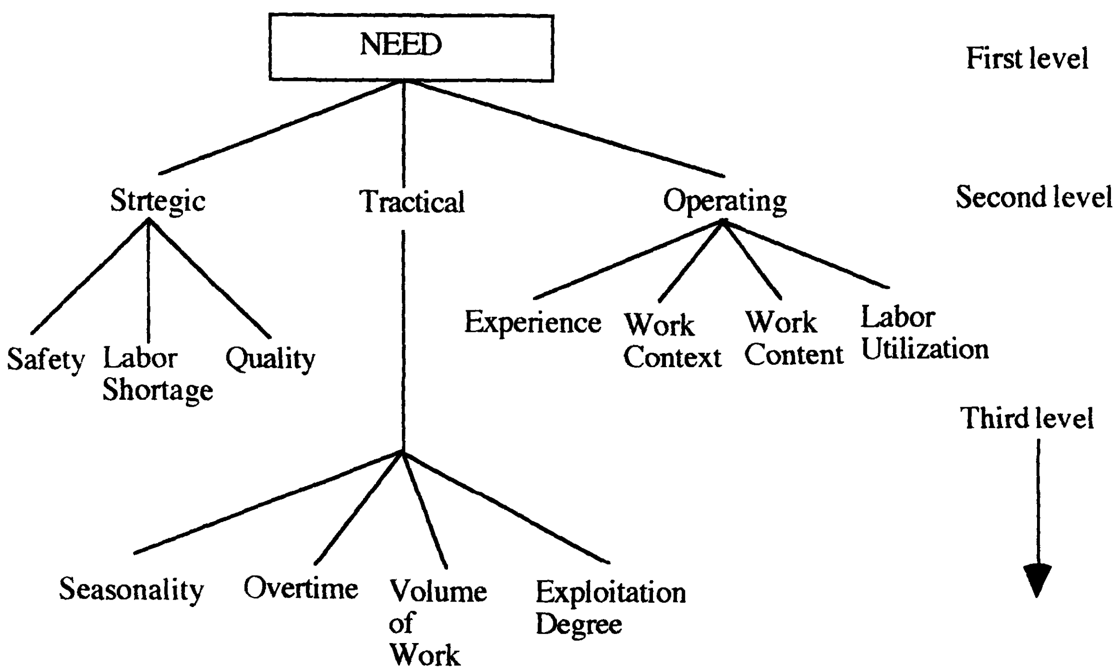

Figure 3.1 Automation index model

[52] Fazio, Paul "Automation Index for Evaluation of Robotics Implementation in Construction" the sixth ISARC, p.317
[53] Marazzi, C.A., "A value analysis method for the evaluation of telecommunication system bid proposals" IEEE Transactions on Engineering Management, Vol. 32, No. 2, May 1985
[54] Saaty, T. L. "The Analytic Hierarchy Process" New York, McGraw-hill, 1982

In 1990, Tucker[55] developed and implemented a methodology which included both quantitative and qualitative aspects of construction work in the automation analysis. The quantitative analysis, which is titled Cost Criteria, is shown in Figure 3.2. The qualitative analysis which measures the proclivity of a task for automation has three components: (1) concern analysis (2) severity of those concerns (3) idleness rating. These three components are titled Concern Criteria. Each of these three, the concerns, their severity factor, and the idleness rating, are evaluated separately and then combined into one rating for each task. The concern analysis comprises five concerns: super human handling, safety, quality, productivity, and work force utilization. Each of these concerns is divided into several subcriteria. All the subcriteria include hazardous to health, physically dangerous, elevated work, polluted air space, repetitive, sequential/cyclic, dirty/unpleasant work, weather impacts, tolerance levels, consistence/repeatability, requires specialized skills, more than one person needed, tedious/boring/exhaustive, meticulous work, heavy lifts, high lifts, and physically exhaustive. This methodology used questionnaires to collect information for qualitative analysis and field data collections for quantitative analysis.

(Field Data Worker Hour - %) X (Model Plant Data - %) = Cost Impact

Figure 3.2 Cost Impact Computation

In 1992, Yuan-E Then[56] suggested a matrix form for classification system for construction automation which constitutes nine various projects and sixteen techniques to

[55] Tucker, R. L., et. al., "A Methodology for Identifying Automation Opportunities in Industrial Construction" Univ. of Texas at Austin Sep, 1990, p. 20-55
[56] Then, Yuan-E, "Investigation and Analysis on Automation of Construction Techniques and Equipments" Jun., 1992, p.83-111

identify the priority tasks for construction automation. The nine various projects include bridge construction project, tunneling project, high-rise building project, pavement construction project, runway project, harbor project, dam project, plant and piping project, and underground construction project. Also, the sixteen techniques include survey-control technique, foundation construction technique, excavation construction technique, form work technique, concrete work technique, asphaltic concrete work technique, hoist and installation work technique, integration technique, prefabricating technique, exterior finishing technique, quality control technique, observation analysis technique, anti-pollution technique, and project control and management technique. All the information was collected from questionnaires and interviews with experts. However, his methodology lacks analyses of technical feasibility and economic feasibility and only concerns need feasibility, which contains six levels including (1) the technique is needed import but has no development potential, (2) the technique is needed to import by joint venture with other companies because the importing need large money and the technique has development potential, (3) the technique is needed to import immediately but has no development potential because it only has the needs for the construction market, (4) the technique is needed to import immediately and also to be developed, (5) the technique is needed to import because of the need of the current projects, and (6) the technique is not needed.

In the same year, Askew, Mawdesley and Aldridge[57] used a multi-round postal survey which incorporated Delphi techniques[58] The major objective of the survey was to isolate suitable activities for robotic development, which more accurately reflect the requirements of a specific organization than the methods of initial task identification commonly used by the designers of the hierarchical or feasibility methods. However, the

[57] Askew, W. H., et. al., "Initial Task Selection for Detailed Robotic Evaluation" the ninth ISARC, Jun., 1992 Tokyo, Japan, p. 141-150
[58] Linstone, H. A & Turoff, M., "The Delphi Method - Techniques and Applications", in proc.. 5th ISARC, Tokyo, Japan, p/ 39-46, Jun., 1988

methodology Askew used needs to make several different surveys one by one and the design of each survey is based on the result of the previous survey. Therefore, the disadvantages of this methodology are time-consuming and quite risky because it needs time to sent and receive several different surveys. and if the result of one survey of the several different surveys has a mistake, the rest of the result of the survey will be all wrong.

Guo & Tucker[59] suggested an Automation Concern Index (ACI) for construction task using the Analytical Hierarchy Process (AHP) to assist in identifying automation needs. His AHP structure contains a Automation Concern. five factors and 13 subfactors. Each factor has assigned a weight which is the coefficient of the priority vector derived through mathematical procedures. Based on the mathematical procedures, AHP reaches an objective distribution of priority. Figure 3.3 shows the hierarchy of automation concern. The comparison of these methodologies above is shown in the table 3.1.

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[59] Guo, Sy-Jye and Tucker, R. L., "Automation Needs Determination Using AHP Approach" Automation and Robotics in Construction X, p. 39-46

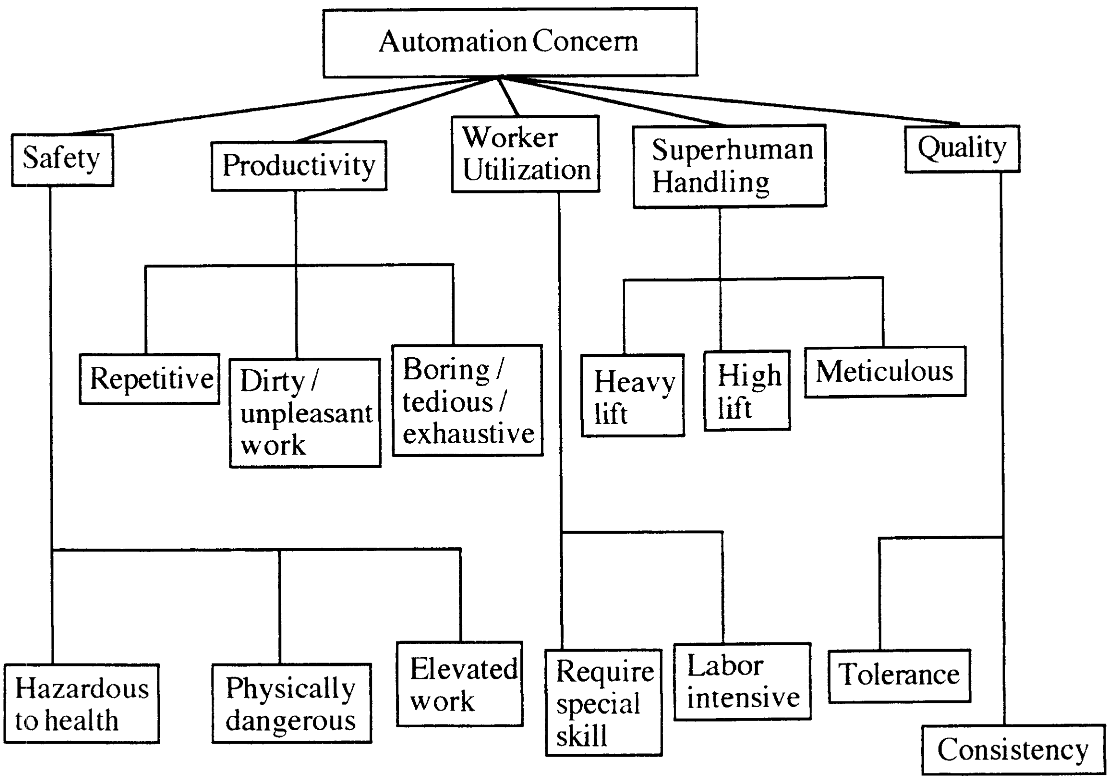

Figure 3.3 Hierarchy of Automation Concern

Author	Methodology	Analysis Factors	Advantage	Disadvantage
Kangan & Halpin	questionnaires & interviews	need-based feasibility, technological feasibility and economic feasibility, and 18 subfactors	1. simple, time-saving 2. including and analyzing need-based, technological and economic feasibility in just one analysis table	1. the respondents must have very strong background or experience about construction automation 2. the weight factor which is the multipliers for rating is subjective and not suitable to other region 3. lack of field data to prove the quantity from questionnaire 4. lack of consensus of analysis scale from experts
Koskela, Lempinen and Salo	interviews	functional factor and preliminary technical factor	1. simple and time saving	1. lack of need-based and economic feasibility 2. lack of practical quantity analysis 3. lack of consensus and objectivity of analysis scale from experts 4. the respondents are limited to seven themes which were already selected
Paul Fazio	surveys and information research from C.S.S.T. and C.C.Q.	three levels for automation index, first level is need; second level contains 3 factors; the third level has 11 subfactors	1. simple 2. efficiently apply the accurate quantitative data from C.S.S.T. and C.C.Q.	1. lack of technological and economic feasibility 2. the respondents must have very strong background about construction automation 3. lack of consensus of analysis scale from experts
Richard L. Tucker	questionnaire for qualitative analysis and site observations for quantitative analysis	(1)qualitative analysis includes the severity factor, idleness rating, and concern analysis which comprises five concerns and seventeen subcriteria. (2)quantitative analysis is the cost impact	1. it is more reliable through analyzing the real site observation and labor idleness information 2. it is more feasible for construction automation through analyzing detail tasks	1. time-consuming 2. lack of consensus of analysis scale from experts 3. lack of technological and economic feasibility analysis 4. lack of clear analysis scale 5. the number of subcriteria of each criteria would affect the result of the analysis
Yuan-Li Then	questionnaires to experts	need feasibility is divided into six factors	1. simple and time saving 2. it is more practical on concerning market needed potential 3. it obtained a consensus of analysis scale from experts	1. the respondents must have strong background about construction automation 2. it may not correlated between column and row in the matrix table 3. lack of technological and economic feasibility analysis
Askew, Mawdesley and Aldridge	multi-round postal survey which incorporated Delphi techniques	4 major analysis factor: disruption, benefit, restriction, and desire	1. it is not limited by subjectively chosen tasks 2. simple and less prejudice	1. it is time-consuming by multi-round surveys 2. lack of technological feasibility analysis 3. the respondents must have strong background about construction automation

Table 3.1 Comparison of the Current Methodology for Identifying Automation Opportunities in the Construction Arena

Author	Methodology	Analysis Factors	Advantage	Disadvantage
Sy-Jye Guo and R. L. Tucker	direct field investigation and interviews with field personnel which incorporated AHP	5 major factors, weight and cost effect	1. it resolves the argument of subjective weights and researches an objective distribution of priority. 2. it is more reliable through direct field observation and labor idleness information	1. time-consuming 2. only cost effect value and need factor, lack of technological and economic feasibility analysis

Table 3.1 Comparison of the Current Methodology for Identifying Automation Opportunities in the Construction Arena (cont'd)

3.3 INTRODUCTION TO THE ANALYSIS APPROACH

The construction industry, in general, has been traditionally conservative in accepting new approaches. It appears that the rule of evolutionary, rather than revolutionary, change will continue to hold, and that acceptance of robotization will necessarily be proceeded by an automation phase.[60] That is, technology leading to a higher degree of machine and equipment automation will have to yield productivity improvement higher than a skilled worker before full robotization will be accepted in practice.

The approach presented in this chapter provides the basic elements needed in a decision making process, that could be undertaken by manufacturer-suppliers, contractors, government, and academic institutions, for evaluating areas of promising robotic implementation. Since examining various methodologies which relate to the feasibility of construction automation, a new methodology, supplemented by industry experience obtained through surveys, was designed. The flow of the analysis is shown in figure 3.4. the major factors during the adoption of automation in construction are identified as the following:

[60] Kangari and Halpin "Potential Robotics Utilization in Construction" JCEM, Mar, 1989, p.126

(1) need-based feasibility

(2) technological feasibility

(3) economic feasibility

These three components constitute the feasibility analysis.

The next section begins with a discussion of the information collection techniques utilized during this research, followed by the methodology of the matrix analysis. The three primary factors will also be described in detail.

3.4 INFORMATION COLLECTION TECHNIQUE

Among the methodologies researched, the use of questionnaires is very common. The advantages associated with the use of these techniques are: (1) direct personnel interaction, (2) relatively inexpensive, and (3) large data base possible.[61]

Direct interaction with management and field personnel is important because the people who work in the field environment on a daily basis are better-qualified to make judgments about field problems in construction than others because they must constantly adjust their methods and schedules to accommodate difficult situations and/or lack of proper materials and equipment. Management personnel can also offer many insights into the problems that they consider important due to their knowledge of cost and schedule information. The use of questionnaire is relatively inexpensive because the researcher is not required to travel to each construction site. By sending questionnaires through the mail a much larger audience can be reached and a greater cross section of the industry is thus

[61] Tucker, R. L., et. al., "A Methodology for Identifying Automation Opportunities in Industrial Construction" Sep..., 1990, p.12-15

included in the resulting statistics. A summary of these methodologies is presented in table 3.2.

From the table 3.1 and 3.2, it is explicit that many researchers have used questionnaires. Meanwhile, based on the advantage of the questionnaires and its wide acceptance by many researchers, the information collection method for the research of this thesis is designed to be questionnaires.

3.5 THE METHODOLOGY OF MATRIX ANALYSIS

In construction projects, it is very common that construction techniques or tasks are used in various construction projects. For instance, the excavation construction technique is used in bridge, tunneling, high rising building, harbor, dam, and underground construction projects. However, the excavation construction techniques and tasks used in various projects contain differences. Therefore, the techniques or tasks can not be divided and delimited into a hierarchical structure. Thus, the Analytical Hierarchy Process (AHP) is not suitable for the characteristics of construction industry. However, the matrix analysis method could solve this problem.[62]

This research focuses on the identification of potential construction techniques for automation. In order to use the matrix analysis method, nine major projects have been selected as headings of the columns, and fourteen construction techniques were assigned to headings of the rows in the comparison matrix. Each cell of the comparison matrix then is divided into four cells: (1) need-based feasibility (2) technological feasibility (3) economic feasibility and (4) the status of automation, in order to analyze the feasibility of construction automation for each technique under various projects.

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[62] Then, Yuan-E, "Investigation and Analysis on Automation of Construction Techniques and Equipments" Jun., 1992, p.83-100

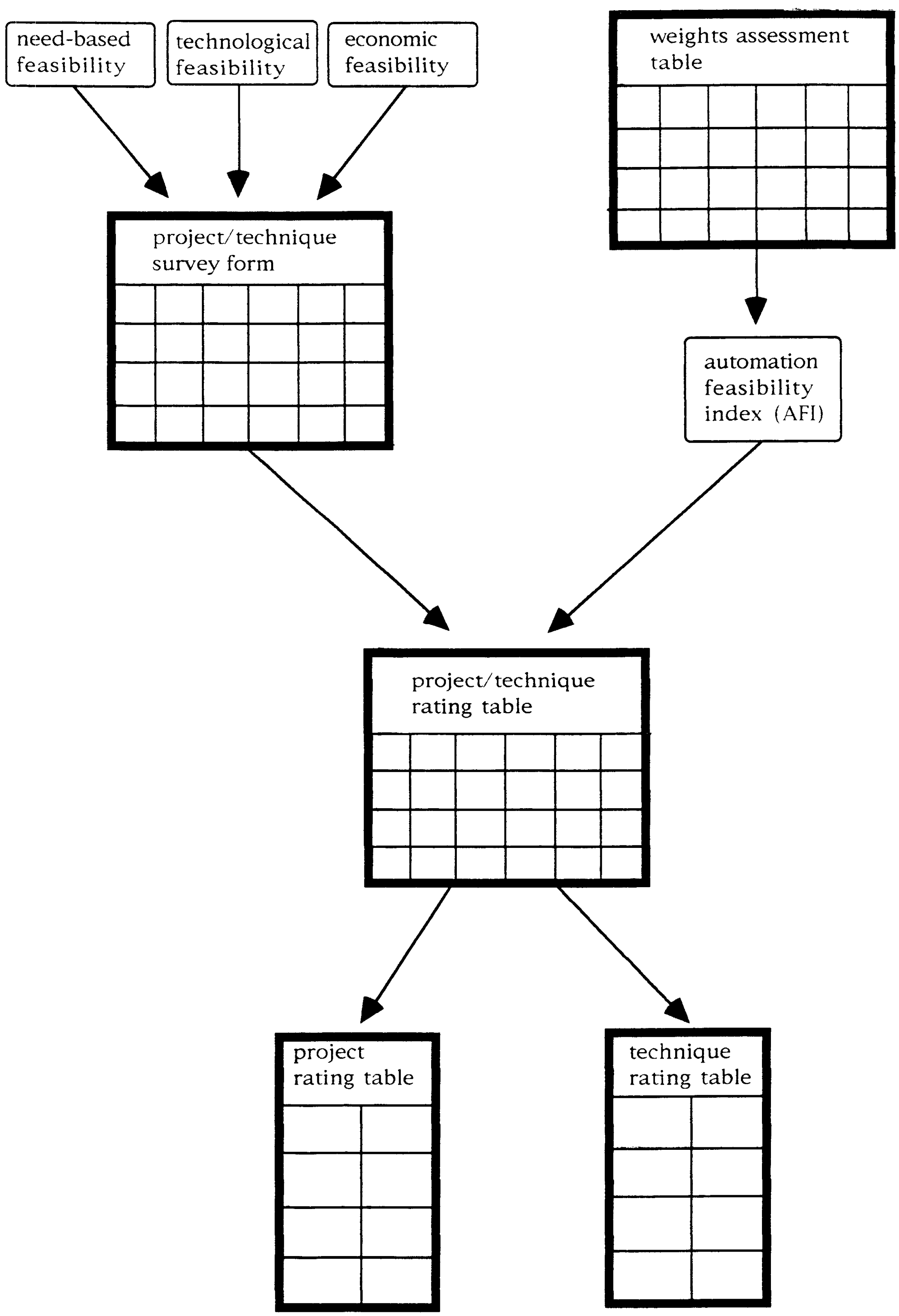

Figure 3.4 Flow of the Feasibility Analysis

TOTAL	Pagadis	Richard & Tucker	Hasegawa	Paulson	Warszawski	Kangari & Halpin	Demsetz	CSTB	Economic Analysis	CREMS	Benefit/Cost	Skibniewski	Tucker & Meyer	RESEARCHER / METHODOLOGY
6	X	X	X			X	X						X	QUESTIONNAIRE/ SURVEY
5	X	X				X	X						X	INTERVIEWS
2			X	X										TIME LAPSE
1													X	SITE OBSERVATIONS
2										X	X			BENEFIT/COST
3	X		X	X										MODEL/SIMULATE
5			X					X	X		X		X	TRADITIONAL METHODS/EQUIP.
3			X								X		X	STATISTICS FROM INDUSTRY/GOVT.
3			X							X	X			REQUIRED ROBOT CAPABILITIES
4						X	X		X				X	RATINGS OR WEIGHTINGS
1									X					DRAWINGS AND SPEC
3	X				X			X						FUNCTIONAL ANALYSIS

Table 3.2 Summary of Methodologies[63]

63 Tucker, "A Methodology for Identifying Automation Opportunities in Industrial Construction", Univ. of Texas at Austin Sep, 1990, p. 20-55

3.6 THE MAJOR FACTORS IN AUTOMATION OF CONSTRUCTION TECHNIQUES

The primary factors driving the adoption of automation in construction are need-based, technological feasibility and economic feasibility. The following sections will describe those in detail.

3.6.1 Need-Based Feasibility

Due to the challenges of construction industry, the needs of reducing labor requirement, safety improvement, increasing productivity, and quality improvement become the motivations of developing CA. Therefore, the objective of need-based feasibility is to determine whether there is a motivation and need to attain higher levels of automation. Halpin & Kangari had noted that closely related to need is the concept of the economic viability of robotization. That is, if the need is sufficiently great, the economic payoff will offset the development expense required to overcome technological barriers.

3.6.2 Technological Feasibility

The second step in the overall effort of evaluating feasibility of automation and robotics in construction is technological feasibility within the conditions of the existing and projected state of the art technology in automation. Several researchers had stated several measuring methods for technological feasibility. Based on the characteristics of the activities, Warszawski & Sangrey[64] defined their technological evaluation which divided robotization into no difficulty, partial difficulty, and most difficulty activities. Kangari &

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[64] Warszawski, A. and Sangrey, D. A.., "Robotics in Building Construction", Journal of Construction on Engineering and Management, Vol.111, No. 3 Sept.. 1985, p.260-275

Halpin[65] believes the technological areas against which each construction process should be evaluated included material handling requirements, required sensor technology, complexity of required control software, control hardware, and end effector requirements. Therefore, the technological feasibility in this research should not only consider present technology but also developmental trends in automation research.(Reinschmidt 1986). The greater the near term availability of a particular support technology, the greater the feasibility of automation.

3.6.3 Economic Feasibility

The most important factor which will be the driving force for practical implementation of robots in construction site is economics of robotization.[66] Analyzing the cost of R&D and economic benefit of applying new techniques in the construction industry could make construction industrial participants understand the advantage and disadvantage of using automated techniques or equipments in order to select appropriate automated system for themselves. However, in general, the economic feasibility is based on the economic benefits which include productivity improvement, quality improvement and savings in skilled labor.[67]

3.6.4 Automation Feasibility Index

The objective of the Automation Feasibility Index(AFI) is to evaluate the feasibility of construction automation. The methodology of assessing weights which are the multipliers of factors including need-based, technological feasibility and economic

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[65] Kangari & Halpin, "Potential Robotics Utilization In Construction" Journal of Construction Engineering and Management, Vol. 115, No. 1, Mar, 1989, p.133

[66] Kangari, Roozbeh, "Advanced Construction Robotics Research at Technology Development Institute of Shimizu Corporation in Japan" Oct. 1991, p.56-72

[67] Kangari & Halpin, "potential robotics utilization in construction" Journal of Construction Engineering and Management, Vol. 115, No. 1, Mar, 1989, p.133

feasibility for calculating AFI is using the concept of the Analytic Hierarchy Process(AHP).[68] The procedure is described as follows:

1. Rank the factors in order and put them as headings of both rows and columns in the comparison matrix. The comparison matrix will have 1 at all the diagonal cells.

2. Compare these factors relatively with a scale of 1 to 5 and fill in the upper half of the comparison matrix based on the discussions and judgment of the definition of the three factors. The scale 1 to 5 represents a ratio comparison of two factors with respect to, (1): two factors contribute equally (2): one factor is slightly more favorable than the other (3): one factor is moderately more favorable than the other (4): one factor is strongly more favorable than the other (5): one factor dominates the other. Table 3.3 shows the comparison of factors.

	technological feasibility	need-based feasibility	economic feasibility
technological feasibility	1	2	3
need-based feasibility		1	5
economic feasibility			1

Table 3.3 Comparison of Factors

3. Put the reciprocal of each cell to the symmetric cell of the lower half of the matrix.

4. Calculate $\sum$ cell value/column sum to calculate a combined weight of each factor.

6. Normalize the combined weight to become a priority vector. The calculation of priority vectors has been present in table 3.4.

[68] Saaty, T. L. "The Analytic Hierarchy Process" New York, McGraw-Hill. 1982

	Technological Feasibility	Need-based Feasibility	Economic Feasibility	Row Sum	Weight
Technological Feasibility	1	2	3	1.50	0.50
Need-based Feasibility	1/2	1	5	1.14	0.38
Economic Feasibility	1/3	1/5	1	0.36	0.12
Column Sum	1.83	3.20	9.00	3.00	1.00

Table 3.4 Calculation of Priority Vectors for AFI

Following the mathematical procedures listed above, a preliminary weight of each factor has been calculated as follows :

Automation Feasibility Index (AFI)

=0.38*Need-based Feasibility + 0.50*Technological Feasibility

+ 0.12*Economic Feasibility

The results of the rating of AFI for identifying potential construction techniques and projects will be presented in chapter 4.

3.7 GENERAL CONCLUSION

To identify the potential techniques for automation in the whole construction industry, the structure of matrix analysis seems more appropriate than the structure of AHP because of the special features of construction industry. Due to the requirement of large data and direct personnel interaction for identification, the method selected for collecting information is survey, which is useful in obtaining a consensus from people who have extensive experience in the field.

In order to evaluate the feasibility of each technique for automation, need-based feasibility; technological feasibility; and economic feasibility are selected as the primary factors driving the adoption of automation in construction. To reach an objective distribution of priority vector which represent an indication of the weight assigned to each factor. the method of AHP is used for deriving priority vector through mathematical procedures.

CHAPTER 4

SURVEY FOR MAJOR CONSTRAINTS AND POTENTIAL TECHNIQUES FOR AUTOMATION IN CONSTRUCTION IN THE US, JAPAN, AND TAIWAN

Based on the reviews of the current situations of construction automation(CA) and the new methodology for identifying appropriate techniques for automation, a questionnaire has been designed for this survey.

4.1 SURVEY OBJECTIVES

This survey is primarily focused on the top contractors in Taiwan, Japan and the US. The main objectives of this survey are:

1. to explore the current situation of construction automation of the top contractors in these three countries.
2. to explore the differences in the way top contractors in these countries develop automated construction.
3. to determine these contractors' specific constraints when developing automated construction.

4. to predict the level of the constraints when developing automated construction in the future.

5. to identify the appropriate construction techniques for automation for the top contractors in these three countries.

6. to measure the willingness of these three countries' top contractors to develop automated construction.

4.2 THE MAIN POINTS OF THIS SURVEY

In order to further analyze the current situation of construction automation in Taiwan, Japan, and the US, and search for the direction of the future development for these countries, it is necessary to consider several main points when designing this survey. These are:

4.2.1 Background of the contractors

This section aims to explore the relationship between the average age of employee in each firm, the size of the firm, the revenue of the firm, and the firm's willingness in developing automated construction.

In this part, the questions are:

1. What is the size of your firm?
2. What was the revenue of your firm in 1993?
3. What is the average age of your employees?
4. How willing are you to apply construction automation? (5 options have been provided: very high, high, O.K.., low, and no need.)

4.2.2. The Owned Ratio

In order to determine the methods of investment of these three countries' contractors in construction equipment, the percentage of current operated equipment which are owned by contractors themselves, equipment suppliers, or clients has been separately asked. Equipment has been divided into 11 major construction categories: excavation equipment, foundation work equipment, drawing equipment, transporting equipment, hoisting equipment, drilling equipment, tunneling equipment, site work equipment, concrete work equipment, pavement construction equipment, and shipping equipment.

4.2.3 Constraints of Developing Construction Automation

The two purposes of this part are: to explore the major constraints for all these three countries; then to find the causes in order to search for solutions to them. However, what is the major constraint? In this thesis, the major constraint is defined as "the constraint which is more serious than other same-year constraints, and which will also become more serious".

The constraints include lack of money, difficulty in finding technical employees, lack of insurance, rejection by labor, difficulty in training , risk of an unstable future in the construction market, lack of appropriate contract provisions, lack of experience in cooperation with international contractor, lack of access to automated equipment supplier, lack of coordination with design plan, lack of turn-key project, lack of support from government, restrictions in laws and policies of government, project too small to apply construction automation, designers discourage construction automation, and recession of the whole industry. The responders assign a rating of 1-5 to each constraint for each year(1992-1996) to provide the information about the level of the constraints when developing construction automation.

4.2.4. The Need-Based Feasibility, Technological Feasibility, Economic Feasibility, and The Status of The Techniques of The Contractors.

The purpose of this part is to explore the potential techniques for automation in major construction projects, based on the analysis of the need-based, technical, and economic feasibility. The detail methodology has been presented in chapter 3.

In concerning the status of the techniques. six choices are provided for contractors to select: 1. traditional construction method(just operated by hands and simple equipment), 2. partial automation(operated by traditional control equipment), 3. automated only control system(operated by distant or remote control), 4. automated system(operated and controlled by using computerized sensing signals), 5. completely automated(operated by AI., no need for human), and 6. none of this technique.

Regarding 9 major construction projects: bridge construction, tunnel construction, high-rise building construction, pavement construction, runway construction, harbor construction. dam construction, plant & piping construction, and underground construction, this survey provides 14 techniques: survey-control technique, foundation construction technique, excavation construction technique, form work technique, concrete work technique, hoist & installation work technique, prefabricating technique, transport technique. exterior finishing technique, quality control technique, prediction analysis technique, observation analysis technique, anti-pollution technique, and project control & management technique for contractors to assign a rating of 1-10 to each technique regarding need-based feasibility, technological feasibility, and economic feasibility. A larger number correlates to a higher level of need, a greater near term availability of a particular support technology, or a reasonable cost and efficiency. This part is designed in matrix form to simplify the description.

The complete survey form is presented in Appendix A.

4.3 THE RESULT OF THIS SURVEY

This survey focuses on the top contractors in Taiwan, Japan, and the US. Based on the result of this survey, the situations and constraints of the various construction automation industries are discussed, and the potential construction technique for automation is identified. Altogether, this research has sent 498 questionnaires and received 56 responses. The total response rate is 11.24%. Among these responses, 16 responses are from the US's contractors, 18 responses from Japan's, and 22 responses from Taiwan's. The results and analyses are described in the following sections.

4.3.1 Result of The Background of The Contractors

Figure 4.1, 4.2, and 4.3 show the background of the contractors who returned this survey. Figure 4.4 shows the willingness of the companies in developing construction automation. Table 4.1 shows the ranking of the background and willingness of the contractors in these three countries.

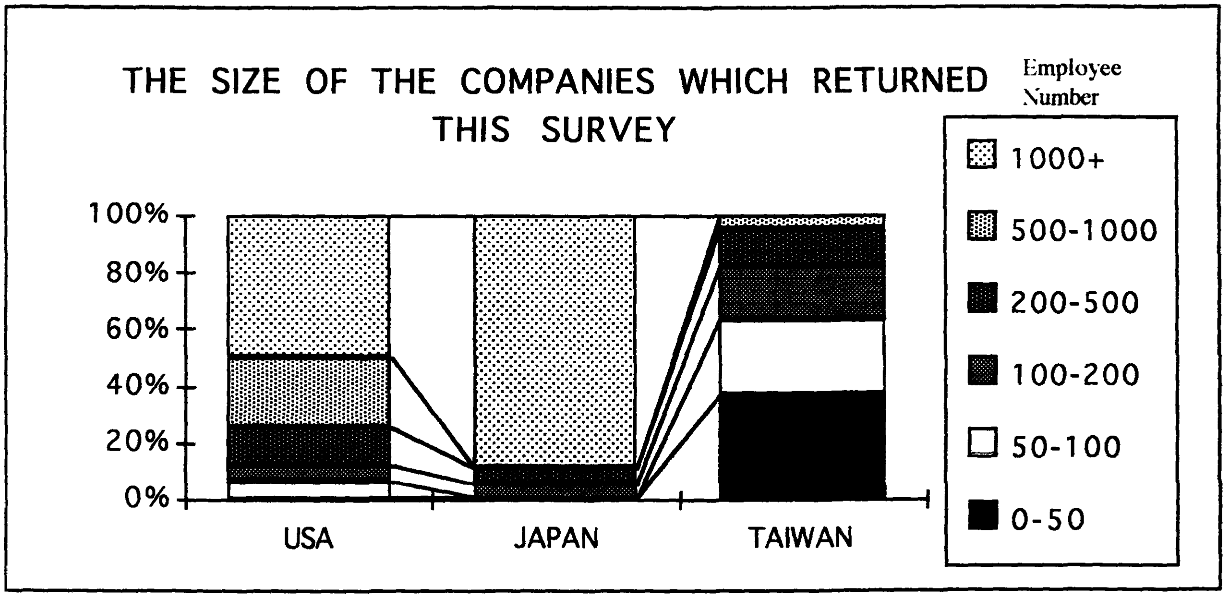

Figure 4.1 Size of The Contractors

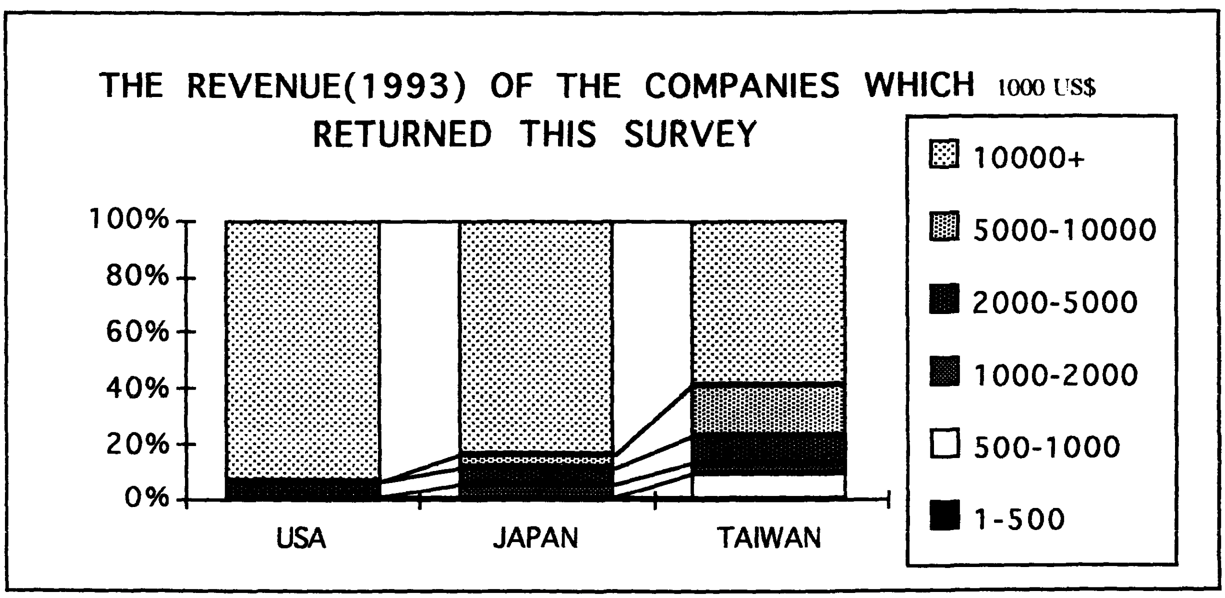

Figure 4.2 Revenue of The Companies

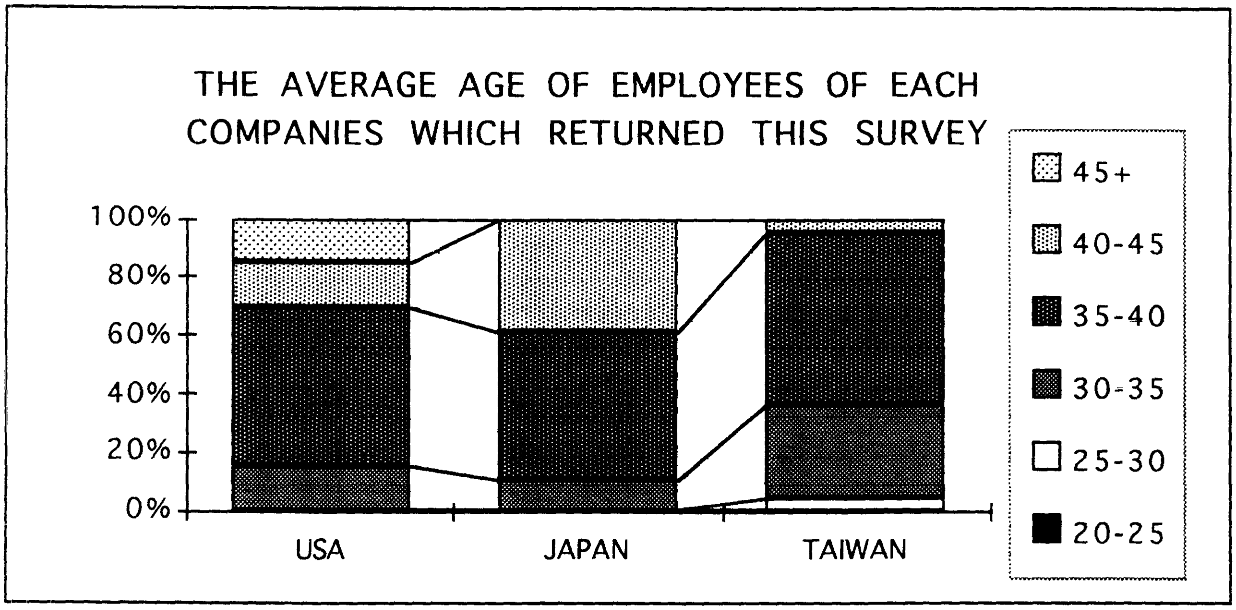

Figure 4.3 Average Age of The Employees

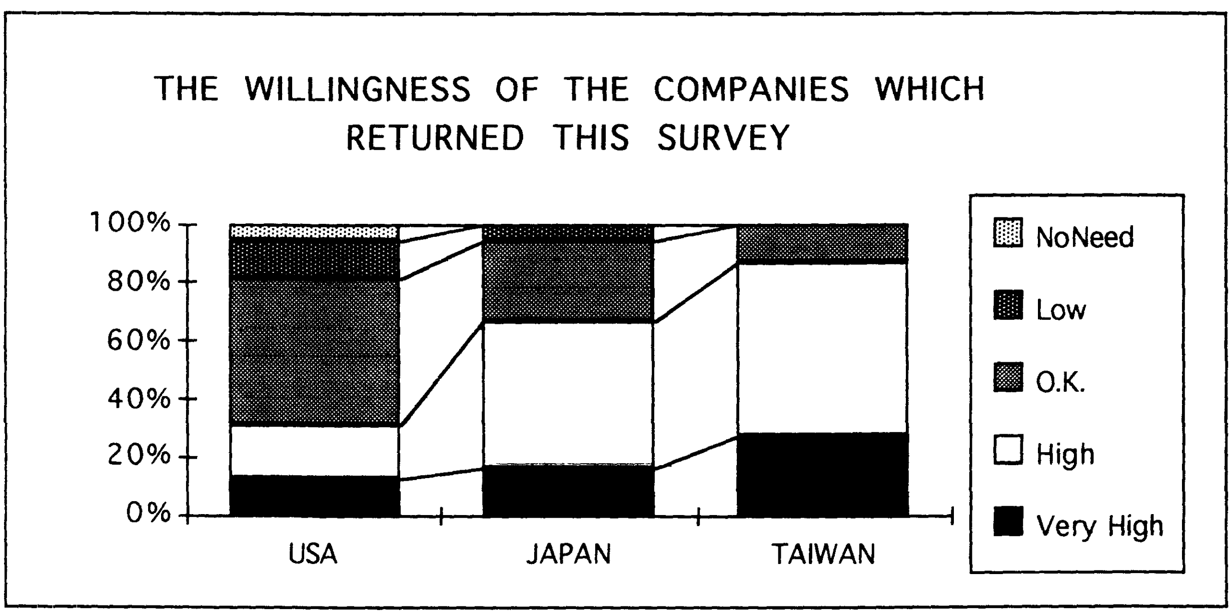

Figure 4.4 Willingness of The Contractors in Developing Construction Automation

Ranking	NO. 1	NO. 2	NO. 3
size	Japan	USA	Taiwan
revenue	USA	Japan	Taiwan
average age	USA	Japan	Taiwan
willingness	Taiwan	Japan	USA

Table 4.1 Ranking of The Background and Willingness of The Contractors

Column NO. 1 indicates the biggest in size and revenue, the oldest in average age or the most willing to develop construction automation. Column No. 3 indicates the smallest in size and revenue, the youngest in average age or the least willing to develop construction automation.

As table 4.1 shows, Taiwan is the most willing to develop construction automation, and the US is the least. The reasons for these differences in willingness ranking are discussed in the following areas.

Most of the top contractors in Taiwan are medium or small size compared to those in the US and Japan, and most of the large construction projects in Taiwan are public. Therefore, the top contractors, who have the ability to develop CA, comparatively rely on the government. Based on that, the encouragement of government is one of the major factors for developing CA. In recent years, because several public construction projects, such as the rapid transit system for Taipei, Taichung and Kaohsiung, are extremely large and complicated, Taiwan's government has encouraged technological cooperation including CA technologies with experienced foreign construction companies This was intended to reduce technological and economic risks in Taiwanese construction projects, and also to promote construction automation. Therefore, under the encouragement of government, more and more construction companies felt the need for construction automation, and the whole construction industry entered the exciting phase of developing CA.

Another reason why Taiwanese contractors are willing to develop CA is that the average age of employees interviewed is younger than those of Japan and the United States; and, younger people are usually more willing to accept new technologies. Therefore, among all the three countries, the willingness to develop construction automation is the highest in Taiwan.

On the other hand, why is the willingness in Japan lower than in Taiwan? Because Japan has already passed the early phase of construction automation. Only a few of the many robots and automated machines, used to promote the company's expertise to clients, have been actually used on the construction site. Moreover. the automated equipment and techniques can not be used for the public construction projects if they are not standardized or designated by the government. As a result, this policy has increased the risk of investment in CA. Therefore, the willingness in Taiwan is higher than Japan. But, why the willingness in Japan is higher than in the US? Several large construction companies in Japan are still very interested in promoting automation because some automated construction systems such as Shimizu's SMART system and Obayashi's T-UP system have already been proven to shorten the duration of construction and reduce labor requirements. On the other hand, most construction companies in the United States have not yet attained real economic benefits from construction automation. In addition, the labor shortage in the US is not as serious as it is in Japan, because the immigration rate of the US is relatively lager than Japan and Taiwan. Many of the new immigrants from Mexico, south America, and Africa worked in the construction industry. Also unions in the US, often acting together as a strong power, oppose any significant automation schemes that might decrease the need for manual labor.[69] Consequently, although several construction companies in the United States are still developing construction automation, the industry's willingness to promote automation is much lower than in Japan and Taiwan.

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[69] Webster, Anthony C., "Technological Advance in Japanese Building Design and Construction" P.98

4.3.2 Distribution of The Ownership of Major Construction Equipments

The results of the distribution of the ownership of the major construction equipment, which are being used by contractors, is shown in figures 4.5, 4.6, and 4.7. The percentages of the contractors' self-owned equipment of the total major construction equipment used by contractors are 55.11% for USA, 24.52% for Japan, and 19.11% for Taiwan. One of the reasons why the ratio for Taiwan is the lowest is discussed in the following section.

Usually, the company's size (including employee number and revenue), of most of the Taiwanese contractors surveyed is smaller than that of Japan and the US. Therefore, the projects they normally have access to contain fewer similar construction projects which would make it more worthwhile to buy than to rent construction equipment. For this reason, most of Taiwanese contractors prefer to rent rather than buy.

However, why does the U.S. have the highest ratio? One reason is that certain kinds of construction equipment are not available on the rental market, forcing contractors to purchase those large and complex machines which are necessary for their projects. Another reason could be that the US's contractors usually want to own the equipment to show their competition, and do not want to rely on the rental companies. Therefore, the ratio for the US is the highest .

Meanwhile, among these three countries, the percentage of the equipment which is owned by clients is the highest in the US. In the US the construction management firms are relatively common and sometimes represent the clients. They order the equipment contractors as well as general contractors for the clients. Therefore, from the contractors' point, some of the equipment they using is rented, owned, or ordered by the construction management firms which are also thought as clients. As a result, the client owned ratio for the US is the highest.

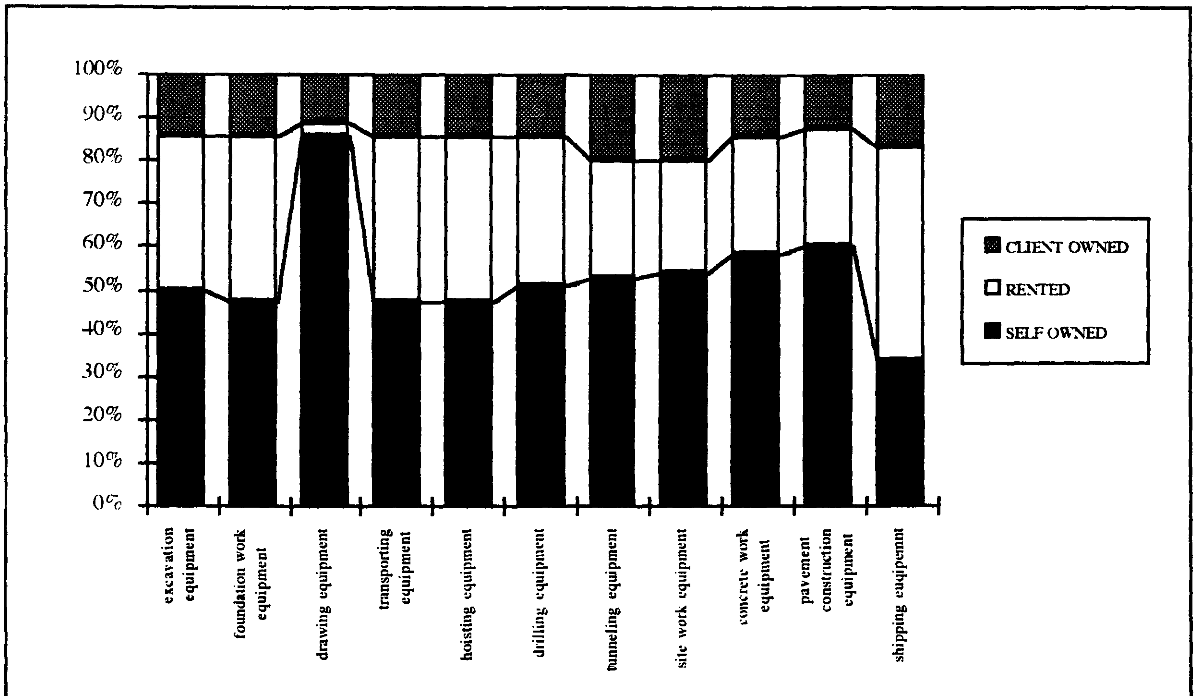

Figure 4.5 Distribution of the Ownership of The Major Construction Equipment Used by US Contractors

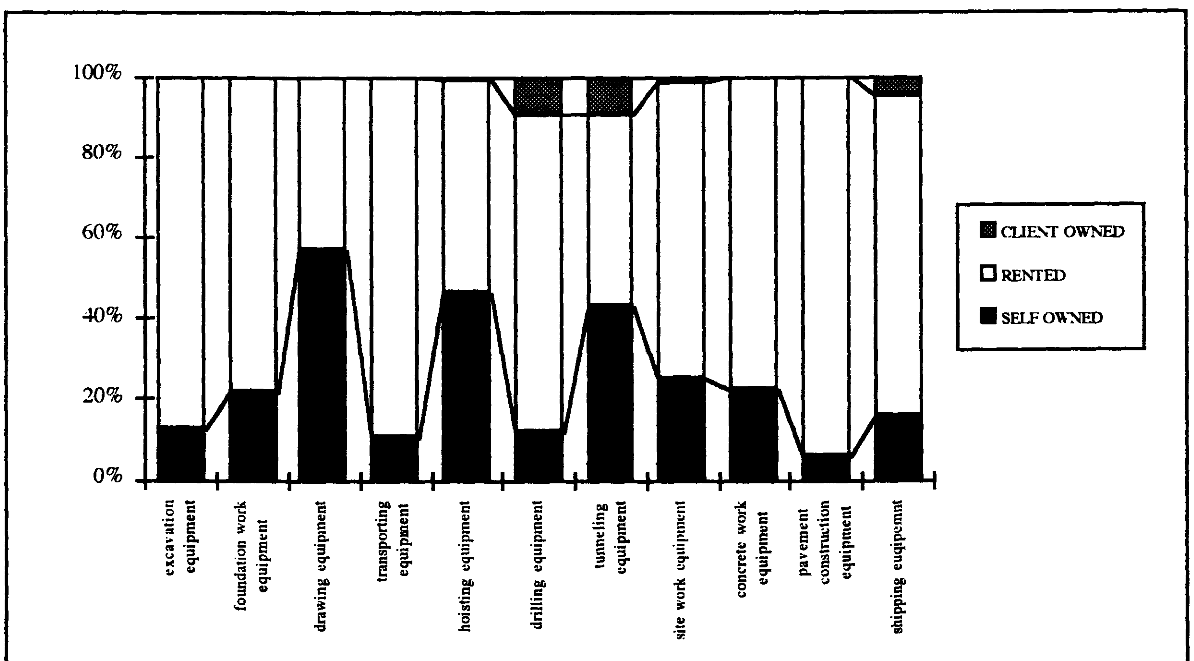

Figure 4.6 Distribution of The Ownership of The Major Construction Equipment Used by Japan's Contractors

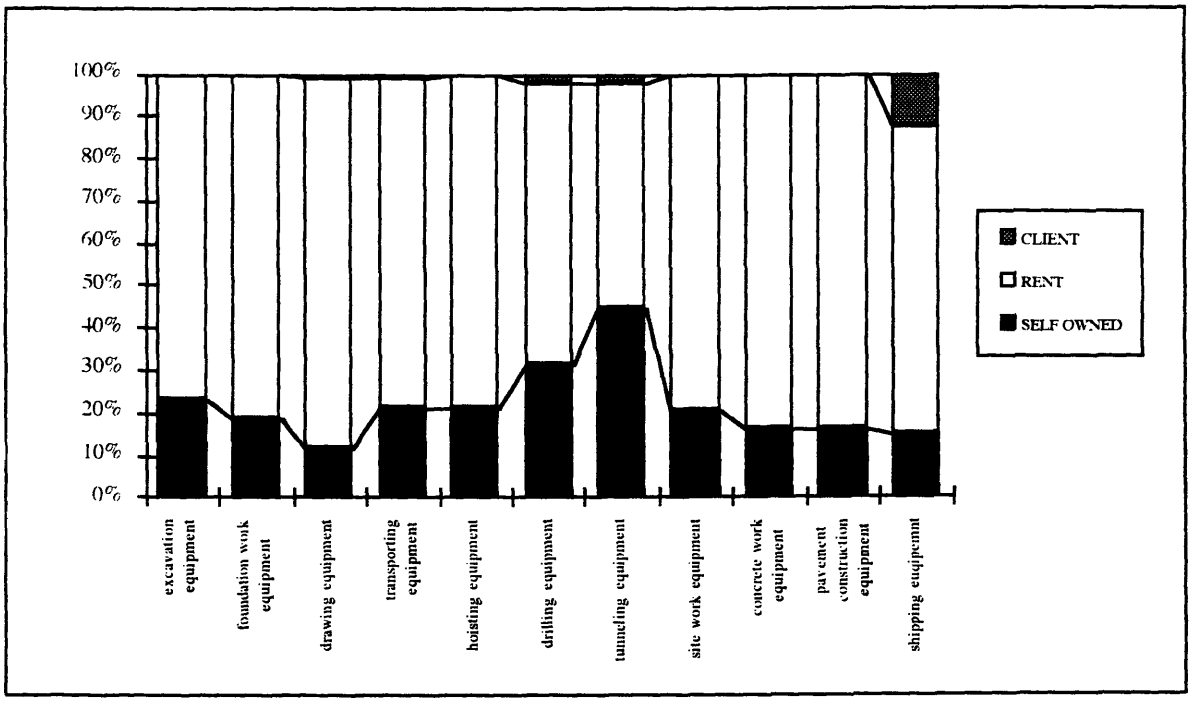

Figure 4.7 Distribution of The Ownership of The Major Construction Equipment Used by Taiwan's Contractors

4.3.3 Result of The Constraints When Developing Construction Automation

Figure 4.8, 4.9, and 4.10 present the average rating for constraints when developing construction automation. Figure 4.8, 4.9, and 4.10 show that these three countries have faced several serious constraints, that some constraints will become more serious in the future, that some will become less serious, and that some will remain stable. The major purpose of this part is to find out the major constraints for these three countries. Among these three countries, "risk of unstable future construction market" is found as the only constraint which will become more serious in all three countries.

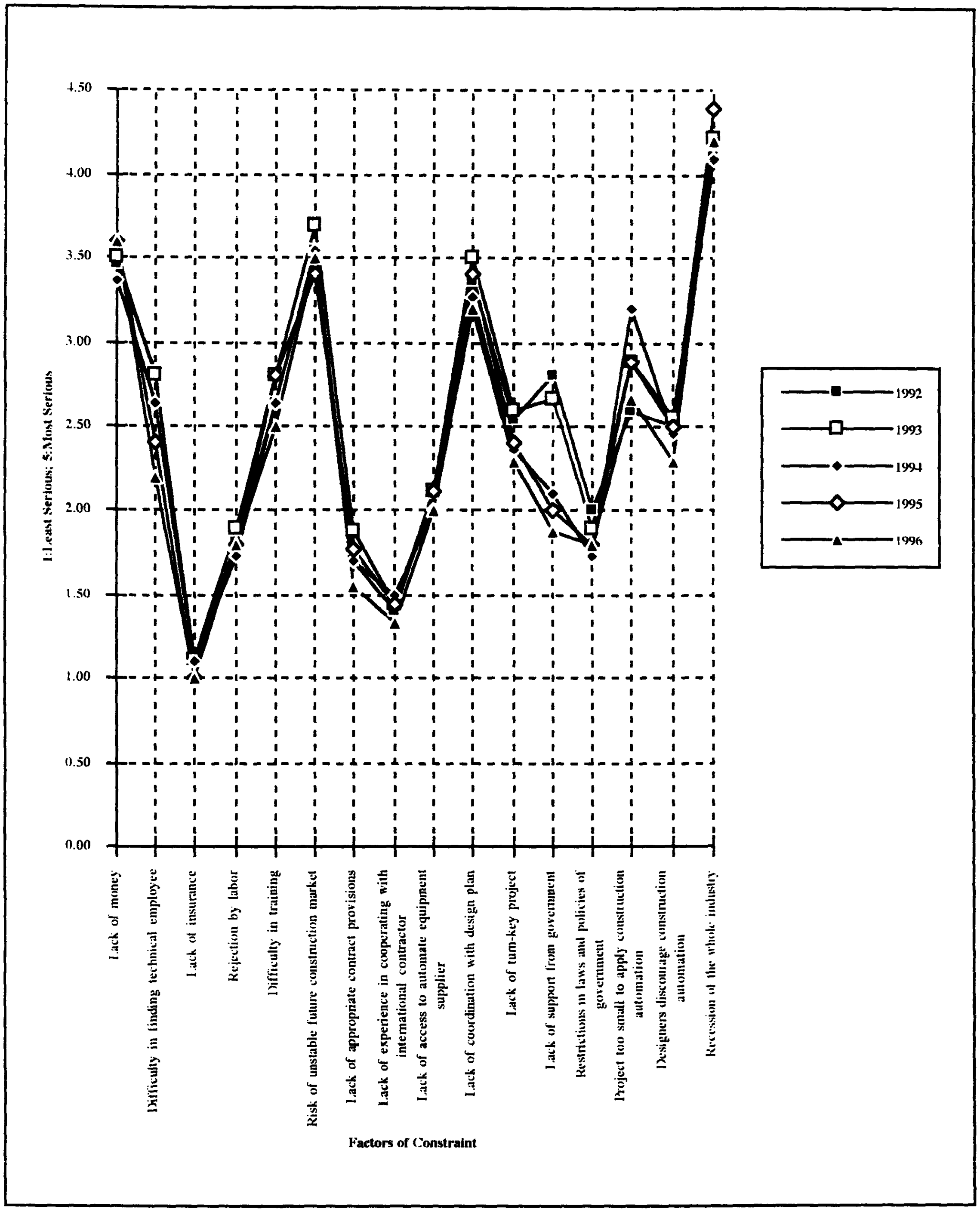

Figure 4.8 Average Rating for The Constraints While Developing Automated Construction from (1992-1996)in The US

As figure 4.8 shows, most of the constraints will remain stable with the passage of time. Only "lack of money", "risk of unstable future construction market", and "recession of the whole industry" are the major constraints which will become more serious in the future. The reasons why these are major constraints are discussed below.

Due to the recession in the whole construction industry, the construction companies are unwilling to make any extra investment in construction automation. Also, from 1991, when the total value of construction dropped from 442 billion US$ in 1990 to 400 billion US$, the construction industry in the US has been in the grip of recession, without signs of future relief. Therefore, "recession of the whole industry" will continue to be one of the most serious constraints when developing construction automation.

Meanwhile, because of the huge investment and long duration for benefit return in the automated equipment and techniques, it is hard to get the real economical benefit. In the US, some organizations have already been developing automation for a decade. However, if considered from an economic view point, most of this development does not have obvious benefit. Therefore, the US's contractors usually invest in CA when they predict they will have several similar projects, which could use the same automated machines. However, due to the continuous recession, the future construction market is more unclear. Therefore, the constraint, "risk of unstable future market", is getting more serious for the US' contractors to develop CA.

Money is always a determining factor when developing CA. It is almost impossible to promote CA without sufficient financial support. However, in the US, traditional sources of government funding for this work such as National Science Foundation, Department of Defense and others, due to federal and state budgetary constraints, will likely remain insufficient for promoting CA.[70] Also the construction industry so far has not

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[70] Skibniewski, Microslow J., "Current Status of Construction Automation and Robotics in The United States of America", 9th ISARC, June 1992, P. 17-24

recovered from the recession. Therefore, money shortage is one of the most serious constraints in the US. and will continue to be a serious major limitation.

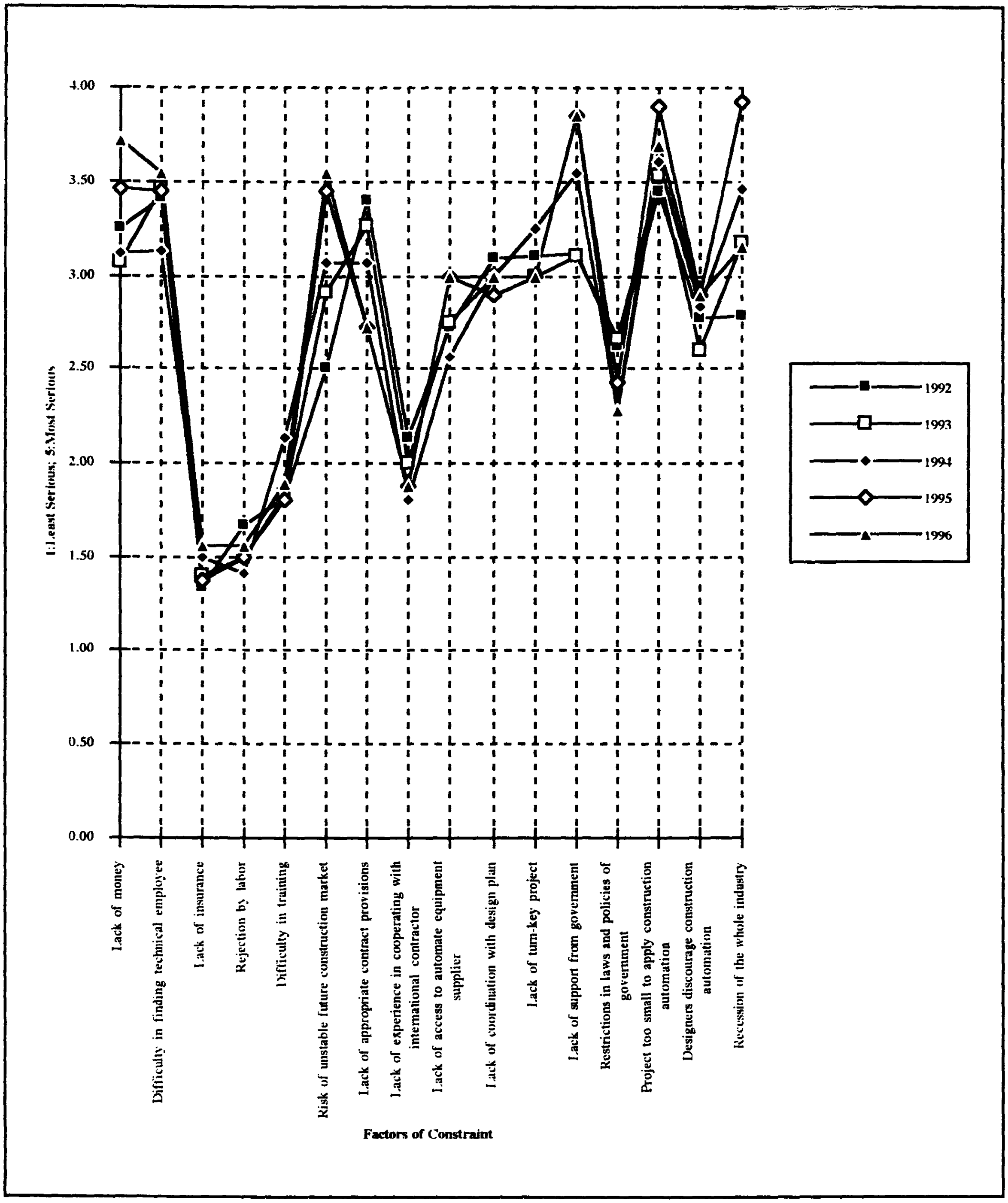

Figure 4.9 Average Rating for The Constraints While Developing Automated Construction from (1992-1996)in Japan

From figure 4.9, the major constraints in Japan were found to be: "lack of money", "risk of unstable future market", and "lack of support from government". The reasons why they are the major constraints are discussed in below:

Since April 1994, the bidding system for public construction projects has changed from nominated bidding system to open-bidding system. In the nominated bidding system, the government usually nominates about 10 contractors. But, more than 30 contractors participate in the open-bidding system. Because of this, the competition is increasing, and the future market for the top contractors has become more unstable. Therefore, "risk of unstable future market" is one of the major constraints. Meanwhile, due to the increasing competition in bidding for a project, the contractors have to spend more money on marketing and estimating. For example, an estimation of a large project would cost about 20 million Yen$.[71] Therefore, the money that could be invested in CA is decreasing, and the constraint, "lack of money", is increasing.

Since the end of bubble economy (1987-1990), the support from government in developing new construction technologies is decreasing. For example, the Ministry of Construction has cut the budget of Joint Research which was established five years ago for developing new technologies under the cooperation of government and private organizations. Therefore, "lack of support from government" has also become a major constraint.

[71] Ibid.

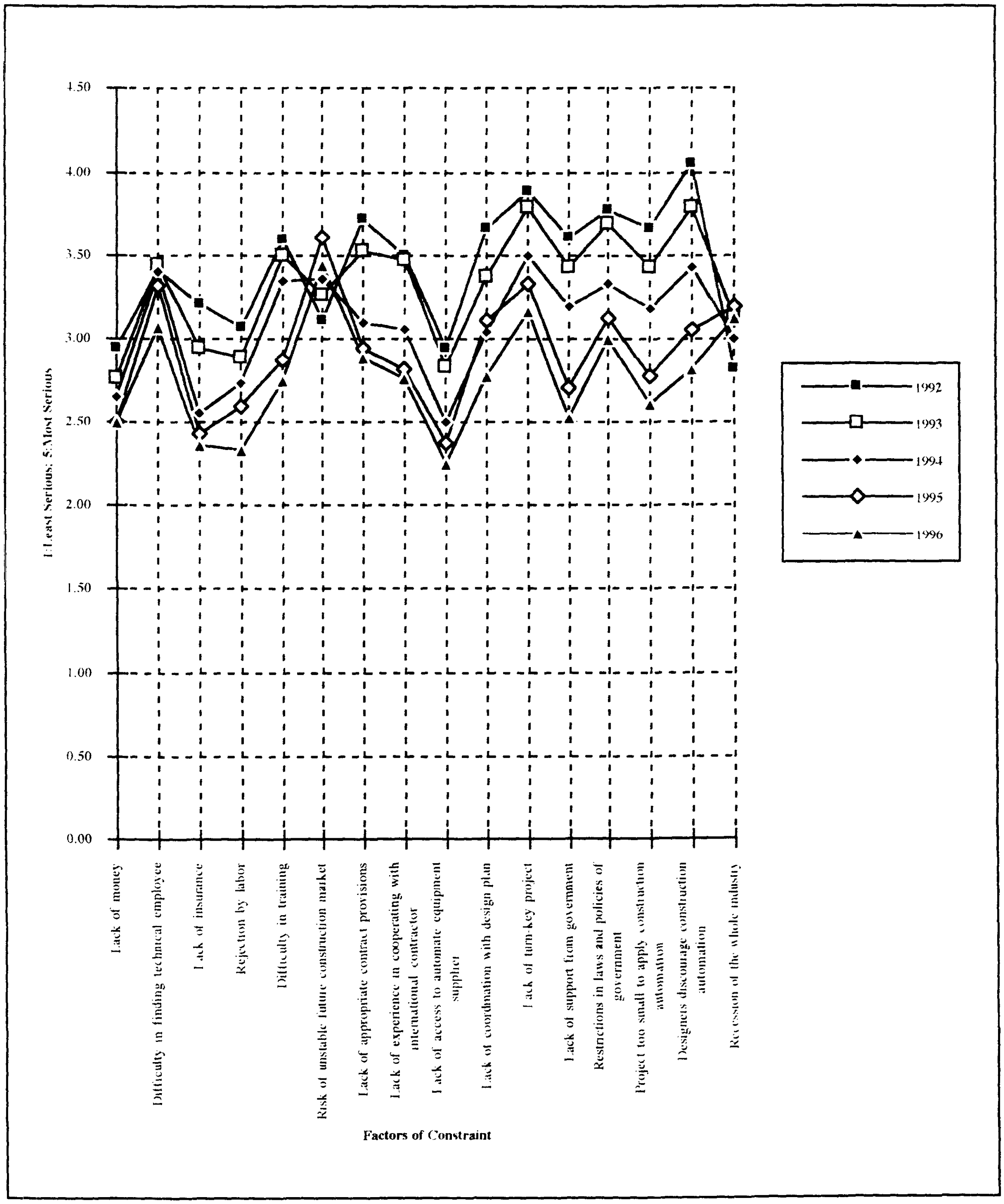

Figure 4.10 Average Rating for The Constraints While Developing Automated Construction from (1992-1996)in Taiwan

From figure 4.10, "risk of unstable future construction market" is found to be the only major constraint which will become more serious in Taiwan. However, why is "risk of unstable future market" a potential problem? Because the features of the construction industry in Taiwan contain unfixed procedures for construction, different sites for different projects, and changeable contractors for clients: therefore, the investment, which includes equipment and other products, of contractors for one project probably would not be useful for another project. Meanwhile, whether they can get the same or similar projects in the future is also unsure. Therefore, "risk of unstable future market" is one of the most serious constraints. At the same time, due to the coming starting phase for automation in Taiwan which is now in the exciting phase, the development of CA will face more difficult challenges. Therefore, the future market is getting more unstable. and the constraint, "risk of unstable future market", is also getting more serious.

4.3.4 Result of The Need-Based Feasibility, Technological Feasibility, Economic Feasibility, and Automation Feasibility Index

This part identifies the potential construction techniques and projects for automation, according to the analysis of the need-based feasibility, technological feasibility, and economic feasibility. However, among the responses from the US, only 25% answered the questions of this part. Therefore, the result from the US on this part could not accurately represent the rest of the respondents. Only the results from Japan and Taiwan are presented in this section. The procedure and methodology of this analysis have been introduced in chapter 3. Table 4.2 and 4.4 shows the automation feasibility index (AFI) for identifying potential techniques for automation in Japan and Taiwan. Table 4.3 and 4.5 presents the need-based, technological feasibility, and economic feasibility of automation in Japan and Taiwan. The techniques of which automation feasibility indexes are greater than 7.60 are defined as high potential techniques for automation. From all the AFI, 7.87 out of a possible maximum of 10 is the highest in Japan, and 7.95 in Taiwan.

	BRIDGE CONSTRUCTION	TUNNEL CONSTRUCTION	HIGH-RISE BUILDING CONSTRUCTION
Survey-control technique	6.43	7.87*	7.51
Foundation construction technique	4.45	4.86	4.94
Excavation construction technique	4.64	7.50	7.04
Form work technique	5.45	5.57	5.27
Concrete work technique	5.40	5.70	5.95
Hoist & installation work technique	6.02	5.48	7.01
Prefabricating technique	6.03	6.02	7.12
Transport technique	5.05	5.04	6.91
Exterior finishing technique	7.43	5.52	6.97
Quality control technique	5.83	5.84	6.28
Prediction analysis technique	6.30	6.27	7.09
Observation analysis technique	5.86	7.28	7.28
Anti-pollution technique	5.75	5.93	6.37
Project control & management technique	6.44	7.14	7.27
* indicates the top three potential techniques for automation; blank cell indicates that the respondents felt no relationship between the technology and the matched project			

Table 4.2 Automation Feasibility Index for Identifying Potential Techniques for Automation in Japan

	PAVEMENT CONSTRUCTION	RUNWAY CONSTRUCTION	HARBOR CONSTRUCTION
Survey-control technique	6.78	6.78	6.68
Foundation construction technique	4.50	4.33	6.45
Excavation construction technique	5.50	5.04	6.06
Form work technique	6.83	6.18	5.11
Concrete work technique	5.75	5.91	4.96
Hoist & installation work technique	5.00	5.00	4.75
Prefabricating technique	5.45	5.45	6.85
Transport technique	4.50	5.00	5.75
Exterior finishing technique			3.38
Quality control technique	5.87	5.87	5.75
Prediction analysis technique	5.31	6.06	6.75
Observation analysis technique	5.31	6.06	7.05
Anti-pollution technique	6.71	7.67*	6.81
Project control & management technique	6.56	7.44	7.25
* indicates the top three potential techniques for automation; blank cell indicates that the respondents felt no relationship between the technology and the matched project			

Table 4.2 Automation Feasibility Index for Identifying Potential Techniques for Automation in Japan (cont'd)

	DAM CONSTRUCTION	PLANT & PIPING CONSTRUCTION	UNDERGROUND CONSTRUCTION
Survey-control technique	7.44	5.12	7.27
Foundation construction technique	4.31	4.99	6.31
Excavation construction technique	4.86	4.91	7.28
Form work technique	7.40	4.92	5.90
Concrete work technique	6.91	4.75	6.31
Hoist & installation work technique	6.42	5.94	6.06
Prefabricating technique	6.18	7.26	5.88
Transport technique	6.20	6.50	6.40
Exterior finishing technique			5.46
Quality control technique	6.61	6.72	6.44
Prediction analysis technique	6.79	6.47	7.41
Observation analysis technique	6.35	6.47	7.37
Anti-pollution technique	6.74	6.75	7.42
Project control & management technique	7.33	7.78*	7.77*

* indicates the top three potential techniques for automation; blank cell indicates that the respondents felt no relationship between the technology and the matched project

Table 4.2 Automation Feasibility Index for Identifying Potential Techniques for Automation in Japan (cont'd)

	Need-Based Feasibility	Technological feasibility	Economic Feasibility
Survey-control technique	5.98	7.54*	6.97*
Foundation construction technique	4.94	5.10	4.92
Excavation construction technique	5.59	6.12	5.72
Form work technique	6.38	5.62	5.11
Concrete work technique	5.63	5.87	5.52
Hoist & installation work technique	5.58	5.94	5.43
Prefabricating technique	7.20	5.73	5.37
Transport technique	5.61	5.81	5.57
Exterior finishing technique	6.37	6.18	5.47
Quality control technique	5.70	6.45	6.18
Prediction analysis technique	6.05	6.81	6.58
Observation analysis technique	6.13	6.91	6.45
Anti-pollution technique	6.24	7.00*	6.75
Project control & management technique	6.61	7.71*	7.08*

* indicates the major factors which make the matched technique become potential for automation

Table 4.3 Feasibility of Major Techniques in Japan

From table 4.2, the high potential techniques for automation have been found. They are survey-control technique in tunnel construction. project control and management technique in both plant and piping construction and underground construction, and the anti-pollution technique in runway construction. The reasons why those are the potential techniques for automation are primarily because they contain high economic benefits and great near term availability of a particular support technology for automation, as shown in the table 4.3.

However, why do the techniques contain high economic benefits and great near term availability of a particular support technology? In order to answer this question, the automated tunnel face marking technique has been selected as an example of automated survey-control techniques in tunnel construction. Automated marking technique usually needs a marking device which irradiates the excavating profile, and a controlling computer. The technologies required for automated marking device are relatively simple, and well developed in Japan. Therefore, as a result, the survey-control technique could also be proven to obtain a high technological feasibility rating. Also, automated marking technique could provide precise instruction on the excavation profile, for allowing accurate excavation, reduced over-breaking excavation, and an enhanced economy.[72] Therefore, it has high economic benefits.

The major technologies for automated project control and management techniques in both plant and piping construction and underground construction are expert system, information network data processing and computer aided drawing/design(CAD).[73] Those technologies have already been well developed in Japan. Also, because usually there are many uncertainties in underground construction, and most of the pipe and plant

[72] Kaneda and Fukuda, "A New System for Marking off on The Face in a Tunnel", the 9th ISARC, June 1992, Japan, P. 645-650

[73] Miyatake and Kangari, "Experiencing Computer Integrated Construction", Journal of Construction Engineering and Management, Vol. 119, No. 2, June, 1993, P. 307-322

construction projects hire engineering consulting firms and contractors separately, the role of the project control and management become more important. with the use of automated project control and management techniques, the uncertainties at the construction stage which usually cause delays in schedule and the loss of money could be reduced. Therefore, the project control and management techniques in both plant and piping construction and underground construction are appropriate for automation.

The primary technologies and devices for automated anti-pollution techniques in runway construction are laser ablation, atomic emission spectrometry, robot arm, surface sampling probe, subsurface sampling probe, compressed gas, rotating brushes, and the ultrasonic bath.[74] These technologies and devices have also been well developed in Japan. Therefore, the anti-pollution technique in runway construction has a high technological feasibility rating, and is appropriate for automation.

	BRIDGE CONSTRUCTION	TUNNEL CONSTRUCTION	HIGH-RISE BUILDING CONSTRUCTION
Survey-control technique	5.31	6.51	6.29
Foundation construction technique	5.05	7.33	6.43
Excavation construction technique	5.55	7.95*	6.52
Form work technique	4.55	5.92	5.73
Concrete work technique	5.32	6.40	6.17
Hoist & installation work technique	5.87	6.87	6.18
Prefabricating technique	5.41	6.27	5.79
Transport technique	4.89	5.87	5.37
Exterior finishing technique	4.46	5.64	5.74
Quality control technique	6.66	7.28	6.08
Prediction analysis technique	7.11	7.47	5.65
Observation analysis technique	5.87	7.81*	5.76
Anti-pollution technique	6.35	6.99	5.52
Project control & management technique	6.12	6.49	5.84

* indicates the top three potential techniques for automation; blank cell indicates that the respondents felt no relationship between the technology and the matched project

Table 4.4 Automation Feasibility Index for Identifying Potential Techniques for Automation in Taiwan

[74] Jaselskis, Edward J., "Robotic Soil Sampler for Hazardous Waste Clean Up", the 9th ISARC, June 1992, P. 347-355

	PAVEMENT CONSTRUCTION	RUNWAY CONSTRUCTION	HARBOR CONSTRUCTION
Survey-control technique	4.55	5.48	7.60*
Foundation construction technique	4.61	4.97	6.75
Excavation construction technique	6.32	5.88	7.38
Form work technique	4.45	4.67	6.45
Concrete work technique	4.63	6.52	6.10
Hoist & installation work technique	4.97	5.26	6.33
Prefabricating technique	5.22	5.08	6.63
Transport technique	4.58	5.52	6.40
Exterior finishing technique	3.72	3.34	3.50
Quality control technique	4.89	6.88	6.22
Prediction analysis technique	4.52	5.32	6.60
Observation analysis technique	4.94	5.47	6.17
Anti-pollution technique	5.51	5.98	6.22
Project control & management technique	4.77	4.77	5.51
* indicates the top three potential techniques for automation; blank cell indicates that the respondents felt no relationship between the technology and the matched project			

Table 4.4 Automation Feasibility Index for Identifying Potential Techniques for Automation in Taiwan (cont'd)

	DAM CONSTRUCTION	PLANT & PIPING CONSTRUCTION	UNDERGROUND CONSTRUCTION
Survey-control technique	5.93	5.32	6.45
Foundation construction technique	5.80	5.02	6.25
Excavation construction technique	6.26	5.90	6.56
Form work technique	5.85	5.70	5.34
Concrete work technique	6.30	5.44	6.15
Hoist & installation work technique	5.83	5.61	6.08
Prefabricating technique	5.63	6.03	5.83
Transport technique	5.75	5.05	5.72
Exterior finishing technique	5.27	4.38	4.68
Quality control technique	5.68	5.63	6.15
Prediction analysis technique	5.80	5.58	6.15
Observation analysis technique	5.82	5.65	6.20
Anti-pollution technique	5.82	6.60	6.50
Project control & management technique	5.54	6.13	5.67
* indicates the top three potential techniques for automation; blank cell indicates that the respondents felt no relationship between the technology and the matched project			

Table 4.4 Automation Feasibility Index for Identifying Potential Techniques for Automation in Taiwan (cont'd)

	Need-Based Feasibility	Technological feasibility	Economic Feasibility
Survey-control technique	5.77	6.07*	5.91
Foundation construction technique	5.87	5.64	6.26
Excavation construction technique	6.36*	6.73*	5.82
Form work technique	5.20	5.53	5.53
Concrete work technique	5.77	5.95	6.02
Hoist & installation work technique	6.49	5.59	5.21
Prefabricating technique	5.96	5.77	5.14
Transport technique	5.42	5.41	5.82
Exterior finishing technique	4.59	4.45	4.60
Quality control technique	6.49	5.87	6.37
Prediction analysis technique	6.40	5.73	6.05
Observation analysis technique	6.08	5.82	6.23*
Anti-pollution technique	6.43	6.01	5.97
Project control & management technique	5.57	5.72	5.63
* indicates the major factors which make the matched technique become potential for automation			

Table 4.5 Feasibility of Major Techniques in Taiwan

From table 4.4, the high potential techniques for automation in Taiwan are found to be the excavation construction technique in tunnel construction, the observation technique in tunnel construction, and the survey-control technique in harbor construction. The reason why the excavation construction technique for tunnel construction is the top potential technique for automation is primarily that it has strong need for automation and great near term availability of support technologies. In the case of the observation analysis technique, the reason is that it has high economic benefits. On the other hand, the reason for survey-control technique in harbor construction is that it has great near term availability of a support technology. Table 4.5 has shown the factors which give these techniques high potential for automation.

However, what are the reasons that these techniques have either strong need, high economic benefits or great near term availability of a support technology? The primary technologies for automated survey-control technique for harbor construction are seabed topography scanner, under water boring machine, self-positioning system(GPS, etc.), remote sensing,[75] laser distance sensor, reinforced concrete measuring helicopter, and digital echo sounder.[76] Most of the technologies have been well developed in Taiwan because of the technology transfer between many Taiwanese sensor and scanner manufacturers and foreign experienced companies. Therefore, the technological feasibility rating is high in this technique. In addition, because several extremely large public construction projects, such as the rapid transit systems for Taipei, Taichung and Kaohsiung, need tunnel construction, and the government encourages contractors to develop CA, many projects related to tunnel construction have required automated tunnel excavation techniques. Therefore, the need for automated excavation technique in tunnel construction is strong. Based on the need, many contractors imported tunneling shields and automated tunnel excavation techniques from foreign countries and strengthen the implementation of construction automation. Therefore, some technologies for developing automated excavation technique for tunnel construction have already been transferred from foreign companies and used in Taiwan. This is also the reason for its high technological feasibility rating. Meanwhile, because the automated observation analysis technique in tunnel construction enables a precise measurement for soil discharge quantity and dry sand quantity, and a real time decision;[77] and many tremendous public construction projects in Taiwan are related to tunnel construction, the economic benefits in developing automated observation analysis technique are rapidly increasing. Therefore, it obtained a high rating in economic feasibility.

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[75] Kanzaki, "Projects for Applying Automation/Robotization of Underwater Foundation Work", the 9th ISARC, June 1992, Japan, P.921-929

[76] Onizawa, Itamura, and Ikeda, "Development of Robot for Surveying and Investigation Output of Harbor Structures", the 9th ISARC, June 1992, P. 271-279

[77] Takemura, "Total Shield Construction Control System", the 9th ISARC, June 1992, P. 683-692

4.4 SUMMARY

This chapter focuses on the description of the survey objectives, the main points of the this survey, and the result of the survey. According to the survey objectives and the main points, the questionnaire of the survey has been designed. Based on the analyses of these survey results, the major constraints for these three countries have been found, and the highest potential techniques for automation have also been identified.

CHAPTER 5

SUMMARY AND CONCLUSION

5.1 SUMMARY

Based on the review of the current situations and the development of construction automation in the three countries in chapter 2, the factors of the constraints when developing CA are selected for the design of survey, and the categories of major construction projects and techniques needed for automation are also chosen for the matrix form used for feasibility analysis. Also, after reviewing the various studies of methodologies for identifying potential techniques for automation in chapter 3, a new methodology has been designed. In order to search for the major constraints when developing CA for all these three countries, and the appropriate techniques for automation, a questionnaire has also been designed.

Finally, according to the analyses of the results of the survey, the major constraints of these three countries have been discussed, and the most appropriate techniques for automation have also been identified.

According to the causes of the major constraints, some recommendations for facing and minimizing the constraint could also been inferred. Based on the proper techniques for automation, the future development could be predicted.

5.2 CONCLUSION

Most of the US's contractors prefer to buy equipment than to rent it. However, because of the continuous recession of the industry and the unstable future market, the contractors have become conservative in investing in automated equipment which usually needs long duration for benefit return. Also, because of the insufficient government funding for the development of new construction technologies, and the rejection of applying CA by the labor unions which the contractors rely on and agree to hire all their craft employees from, the contractors in the US felt less interested in developing CA.

On the other hand, because of the change of the bidding system in Japan, the future construction market is becoming more competitive and unstable. Because the larger expense of marketing and estimating with new bidding system, the investment in the CA also relatively decreases. Meanwhile, the government funding for development of new construction technologies has also been cut, and most of the public construction projects do not designate automated equipment and techniques because those equipment and techniques usually lack standardization. Therefore, the development of CA in Japan has faced several challenges. However, speaking of the labor shortage and safety, several Japanese large contractors still believe that the automation is the only way to solve the problem, and they also proved some automated techniques and systems could shorten the duration, reduce labor requirement, and improve productivity and safety. Therefore, the development is still continuous. Recently, the major automation research projects emphasize the survey-control and project control and management techniques. As a result of that, the willingness of contractors in CA is still strong.

In Taiwan, because most contractors are small or medium sized, they usually rely on public projects. Recently several project-oriented contractors increased investing in developing construction automation because several large public construction projects have already required contractors to use automated equipment and techniques. Therefore, the willingness to develop CA is very strong in Taiwan. Also, because several large projects are related to the tunnel and harbor construction, the development of CA also emphasizes the survey-control technique for harbor construction. excavation construction and observation analysis techniques for tunnel construction.

In summary, among all these three countries, the major constraint has been found as "risk of unstable future market", and the most potential technique for automation has also been identified as survey-control technique.

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Appendix A

SURVEY FOR MAJOR CONSTRAINTS AND POTENTIAL TECHNIQUES IN CONSTRUCTION IN THE US, JAPAN, AND TAIWAN

Direction: Please indicate your answers be checking the applicable item(s) after each question or specify other. Thank you for your cooperation.

1. What is the size of your firm?(the number of employee)

____1-50 ____50-100 ____100-200 ____200-500 ____500-1,000 ____1,000+

2. What is the revenue of your firm in 1993?(thousands in US dollars)

____1-500 ____500-1,000 ____1,000-2,000 ____2,000-5,000 ____5,000-10,000 ____10,000+

3. What is the average age of your firm's employee?

____20-25 ____25-30 ____30-35 ____35-40 ____40-45 ____45+

4. How willing is your firm to apply construction automation?

___ very high, ___ high, ___ O.K., ___ low. ___ no need

5. Please indicate a percentage to each equipment

(1) denotes the percentage of the equipment your firm owns.

(2) denotes the percentage of the equipment your firm rents.

(3) denotes the percentage of the equipment which is client owned.

	(1)	(2)	(3)
Excavation equipment			
Foundation work equipment			
Drawing equipment			
Transporting equipment			
Hoisting equipment			
Drilling equipment			
Tunneling equipment			
Site work equipment			
Concrete work equipment			
Pavement construction equipment			
Shipping equipment			

6. Please assign a rating of 1 -- 5 to each constraint below for each year(1992 -- 1996) your firm has faced, is facing, and will face when developing automated construction. A larger number correlated to a more serious constraint.

	1992	1993	1994	1995	1996
Lack of money	____	____	____	____	____
Difficulty in finding technical employee	____	____	____	____	____
Lack of insurance	____	____	____	____	____
Rejection by labor	____	____	____	____	____
Difficulty in training	____	____	____	____	____
Risk of unstable future construction market	____	____	____	____	____
Lack of appropriate contract provisions	____	____	____	____	____
Lack of experience in cooperating with international contractor	____	____	____	____	____
Lack of access to automated equipment supplier	____	____	____	____	____
Lack of coordination with design plan	____	____	____	____	____
Lack of turn-key project	____	____	____	____	____
Lack of support from government	____	____	____	____	____
Restrictions in laws and policies of government	____	____	____	____	____
Project too small to apply construction automation	____	____	____	____	____
Designers discourage construction automation	____	____	____	____	____
Recession of the whole industry	____	____	____	____	____

Applicable items for question 7 :

(A) denotes need-based feasibility

(B) denotes technological feasibility

(C) denotes economic feasibility

(D) denotes the status of the techniques

traditional construction method(just operated by hands and simple equipment)	1
partial automation(operated by traditional control equipment)	2
automated only control system(operated by distant or remote control)	3
automated system(operated and controlled by using computerized sensing signals)	4
completely automated (operated by AI., no need of human)	5
no this technique	blank

7. Please assign a rating of 1--10 to each technique which reflect your opinion regarding need-based feasibility(i.e. driven by need), technological feasibility, and economic feasibility when developing completely automated techniques below. A larger number correlates to a higher level of need, a greater near term availability of a particular support technology, or a reasonable cost and efficiency.

	BRIDGE CONSTRUCTION			TUNNEL CONSTRUCTION			HIGH-RISE BUILDING CONSTRUCTION		
	A	B	C	A	B	C	A	B	C
Survey-control technique									
Foundation construction technique									
Excavation construction technique									
Form work technique									
Concrete work technique									
Hoist & installation work technique									
Prefabricating technique									
Transport technique									
Exterior finishing technique									
Quality control technique									
Prediction analysis technique									
Observation analysis technique									
Anti-pollution technique									
Project control & management technique									

	PAVEMENT CONSTRUCTION			RUNWAY CONSTRUCTION			HARBOR CONSTRUCTION		
	A	B	C	A	B	C	A	B	C
Survey-control technique									
Foundation construction technique									
Excavation construction technique									
Form work technique									
Concrete work technique									
Hoist & installation work technique									
Prefabricating technique									
Transport technique									
Exterior finishing technique									
Quality control technique									
Prediction analysis technique									
Observation analysis technique									
Anti-pollution technique									
Project control & management technique									

	DAM CONSTRUCTION			PLANT & PIPING CONSTRUCTION			UNDERGROUND CONSTRUCTION		
	A	B	C	A	B	C	A	B	C
Survey-control technique									
Foundation construction technique									
Excavation construction technique									
Form work technique									
Concrete work technique									
Hoist & installation work technique									
Prefabricating technique									
Transport technique									
Exterior finishing technique									
Quality control technique									
Prediction analysis technique									
Observation analysis technique									
Anti-pollution technique									
Project control & management technique									