AUTOMATED CONSTRUCTION TECHNOLOGIES:
ANALYSES AND FUTURE DEVELOPMENT STRATEGIES

by

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ABSTRACT

Substandard productivity and the lack of skilled workers in the construction industry have led major corporations all over the world aiming to produce various types of automated construction technologies. During the process, novel ideologies of design and construction techniques have been realized and the push for these applications has never been greater. This thesis will look to answer the question of benefit and effectiveness of automated construction technology. It will focus on three basic concepts: 1) Analyzing existing automated construction technology; 2) understanding of automated machine design and components; 3) proposal of a multi-purpose pick-and-place machine for the automated construction process. In the end, the intention will be to promote a design intensive approach to automated construction technology in order to advance the conventional methodologies of design and construction.

Thesis Supervisor: Lawrence Sass
Title: Assistant Professor of Architecture

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"We can hardly expect to be able to make machines do wonders before we find (out) how to make them do ordinary, sensible things."

Marvin Minsky
MIT, 1982

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PREFACE

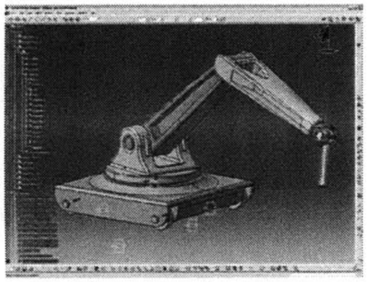
Figure 1 - An early concept for a pick-and-place machine - *Will Lark, MIT*

During the spring semester of 2004, in a Media Lab course called "How to make something that makes almost anything" headed by Professor Neil Gershenfeld of the Center for Bits and Atoms along with Professor Larry Sass of Architecture, Professor Joe Jacobson of Molecular Machines at the Media Lab and Professor Alex Slocum of Mechanical Engineering department at MIT, a concept for a new rapid prototype machine was conceived.

The intention of the class was to rethink the notion of personal fabrication. In the end, our concept was to make a machine that can make an object that is essentially bigger than its own envelope by joining as well as producing pre- fabricated parts. This idea was simple, but largely due to undeveloped technologies in the area of sensors and object recognition, it has never been attempted.

Figure 2 - Working on the design of a pick-and-place prototype - *Summer 2004*

This inspiration shifted into a summer hobby. For three months, my understanding of machines' behavior and their mechanics grew dramatically as I developed and explored several iterations of conceptual prototypes. In the following semester, with the assistant of several mechanical as well as electrical engineering students, I was able to produce an actual desktop-sized semi-operable prototype of the machine. Over the course of the semester, my interest grew larger as my knowledge of robotics, mechanized applications and especially control components of these systems expanded as I worked on the development of circuit boards and programming techniques.

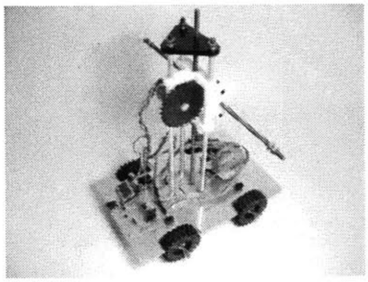

Figure 3 - Working prototype of an early version of the pick-and-place machine - MIT 2004

This exploration in the field of robotics and mechanized systems helped me to realize the general topic of my thesis. Partly due to my background in architecture and having previously worked within the construction industry, my initial thought for this thesis was to mainly analyze and understand the various typologies of automated construction technologies.

Additionally, the primary motivation for my research was solely aimed at creating a new form of rapid prototyping technique by incorporating existing rapid prototyping technologies with real-life construction process. However, during the course of my investigation, the idea of introducing a rapid autonomous delivery process as a real-scale construction method for the benefit of building unique structures, reducing production time, and improving efficiency was overwhelmingly exciting and at the same time logical.

In addition, while studying the overall traditional construction process, it became clearer to me that there were several areas within the hierarchy of the process that were significantly altered when automation was applied. The compression of the construction schedule, reshuffling of various

Figure 4 - Disney Concert Hall construction - *Gehry Partners, LLC - Photo by Grant Mudford*

construction tasks and completely altering the delivery process were particularly compelling and undeniably warranted a closer investigation.

As the result, along with my new found understanding in the areas of mechanical and electrical engineering, I was able to confidently attempt to search for new automated application typologies that were not only adaptable to the world of rapid prototyping technology, but also to the advancement of production in the design and construction industry. This led to a proposal for a new automated system that can potentially alter the way in which the construction industries, as well as the design profession, approach the notion of conception and production.

This concept was never considered or attempted for many reasons. First and foremost, due to the slow progress of technological development in the field of robotics, "intelligent" machines are difficult to achieve. Secondly, not until the realization of the success with the rapid prototype engineering techniques, many researchers are leaning towards advancing these types of methodologies into other disciplines especially full-size scale construction process[1]. And finally, in terms of interface between design and assembly, with recent advancement in the development of software applications[2], manufacturing solutions for digital product definition, collaboration, fabrication processes and digital product simulation of all sizes can now be easily realized.

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[1] A process called Contour Crafting (CC) developed by Dr. Behrokh Khoshnevis at USC is a perfect example of this adaptation from prototyping technology to the construction industry. Please refer to Chapter 2 (2.4.2) for more details on this process.

[2] This is in reference to a software application called CATIA which stands for Computer Aided Three-dimensional Interactive Application developed by Dassault Systems and IBM that encompasses solutions for digital design to manufacturing.

CHAPTER 1:
INVESTIGATION AND ASSESSMENT

1.1 Industry Problem

Architectural design and construction are considered to be among the oldest and largest industries in the world. Despite of this fact, they are still regarded as the least advanced industries in the utilization of innovative technology, which is available for the performance of design and industrial processes. Largely, this is due to the slow rate of progress in the automating process[3].

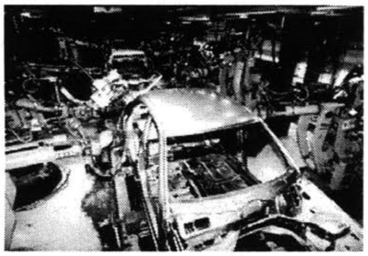

Figure 5 - Automotive assembly factory - *Photo by Jay O'Brien*

The construction industry lags behind other industries, for instance the manufacturing industry, and in particular, it falls

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[3] In reference to an article written by FIATECH on Intelligent & Automated Construction Job Site. Element 4 Tactical Plan for the Capital Projects Technology Roadmap. 2004. For more information, please refer to http://www.fiatech.org/projects/roadmap/jobsite.html

short of the automotive industries in terms of automation. Tools for automated information processing in areas such as design development, communication, and production have long moved into the stages of design and engineering, but have not yet found their way to the construction site.

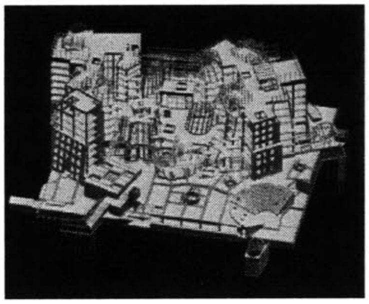

Figure 6 - 3D Master model of the Stata Center at MIT - *Gehry Partners, LLC - Gehry Technologies*

A major dilemma for the construction industry is that the information that is required at the site has become more complicated, but traditional labor-intensive processes are still being used. The type of machinery and application with the technology to process this type of information doesn't exist today, which limits all facets of construction execution in terms of effectiveness and productivity.

1.2 Vision of a New Process

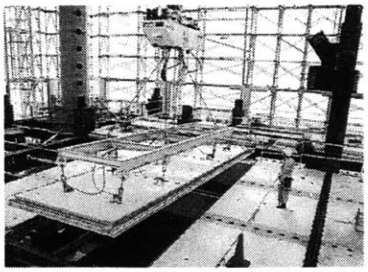

Figure 7 - Floor panel installation by the SMART automated construction system - *Shimizu Corporation, Japan*

This thesis presents several analytical perspectives on the methodology and implications of technologically driven applications and automation of the construction process. The design and construction processes of the future will take full advantage of the ever-increasing information and automation technologies to advance the level of quality, efficiency, technical performance, and safety.

Design, construction, as well as manufacturing and on-site application techniques will become more intelligent and integrated as tools, equipment, materials, and people become a cohesive component of a fully observed and technologically controlled construction environment.

Advancement in the applications of design and integrated automated construction processes will not only eliminate manual labor in hazardous working conditions, but also take full control of labor-intensive tasks. Construction job sites will be networked with communications technologies that will enable sophisticated machinery along with capable workers to perform their jobs rapidly, precisely, and more effectively. In order to realize a more cohesive, productive, and effective process for design and construction, one needs to incorporate novel automated methodologies and techniques into the process.

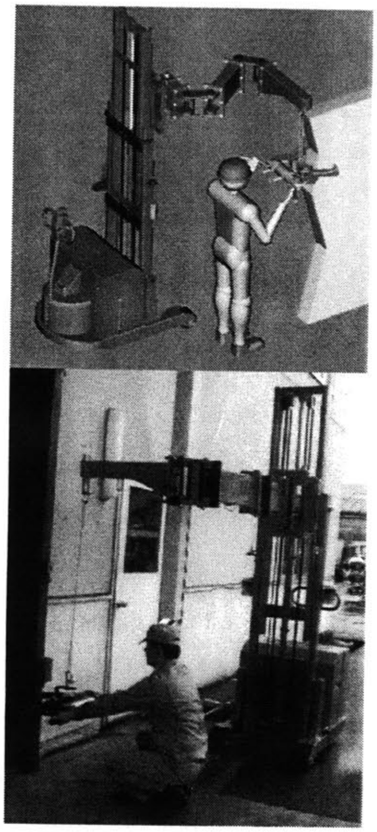

Figure 8 - A multi-purpose construction robot currently is being developed by *Hitachi* in conjunction with *Shimizu Corporation - All rights reserved by Hitachi Construction Machinery Co., LTD.*

1.3 Thesis Organization

Since this thesis is structured around the analyses of existing automated construction technologies, it is crucial that majority of what is being written needs to focus on analyzing and discussing these technologies. Majority of the technologies were discovered in person through visual demonstrations during a visit to Japan's leading construction corporations specializing in the field of automated technologies. A summary of these findings are significant for the understanding of the physical mechanics and overall working properties of the latest advancement in automation.

Once the consideration of the unique applications within the automated construction technologies have been established, the discussions of rapid prototyping engineering techniques are revealed. This section describes the direct effects between the current automated construction technologies and the rapid prototyping methodologies. Following this topic is a proposal for an entirely new system of development for the advancement of automated construction incorporating the two principles.

Although several key components are beyond the scope of this research, nevertheless, an entire system for an automated design approach is introduced from beginning to end. Along with this proposal, summaries are developed of machine typologies and the inner workings of robotics and their design methodologies. Several unique robotic systems are discussed and analyzed for the benefit of understanding the different options that are necessary when designing an automated construction machine or robot.

1.4 Research Approach

The traditional construction process comprise of procedural categories ranging from scheduling within the preliminary phases to the physical installation of various control systems. In order to recognize the reasons for the demand of automated construction tasks, a hierarchical map of a typical construction process was laid out. In addition to recognizing the motive, the map also provided an understanding of the many levels and stages between the traditional and automated construction procedures. Through the visual comprehension of the construction process and the analysis of current development in automated technologies, logical interests within the areas of automated techniques are revealed.

Several perspectives of materiality, manufacturability, and constructability are taken into considerations within the hierarchy of the construction process. These viewpoints demonstrate not only the separation of procedural categories, but also recognition of the conventional construction delivery process. With the realization and consideration of these divisions, the possibilities for altering and mixing the typical pattern of the process become much more natural and warranted.

Since the majority of the automated tasks are driven to enhance efficiency and productivity, several categories that were especially dependent on the intricacies of manual labor have now become irrelevant. These ideologies not only change the entire hierarchy of the construction process, but furthermore, they altered the inter-relationships that involve every aspect of design, manufacturing, and construction.

1.5 Method of Investigation

The main strategy of this thesis is to incorporate novel mechanized methodologies and techniques into the automated construction process. Additionally, it aims to promote a design intensive approach to the construction procedures with the intention of maximizing performance. In order to do so, it is necessary to understand the significant changes from the reorganization of the traditional construction process, as well as the insight of existing automated technologies and the knowledge in the advancement of unique engineering techniques. These factors are combined with the main objective of advancing the conventional process of design and construction.

A key advantage to this understanding was derived from an actual visit to two very impressive research institutes in Japan. Through physical analysis of currently automated systems and the investigation of machines and robotics technology, new understandings and appreciations for conception and production of construction and machinery were formulated. In addition, the available resources and the cross-disciplinary nature of MIT's curriculum were not only beneficial, but also effective for the purpose of compiling a comprehensive academic research. With this foundation in hand, the path to discover the next generation of automated construction technology is conceivably obtainable.

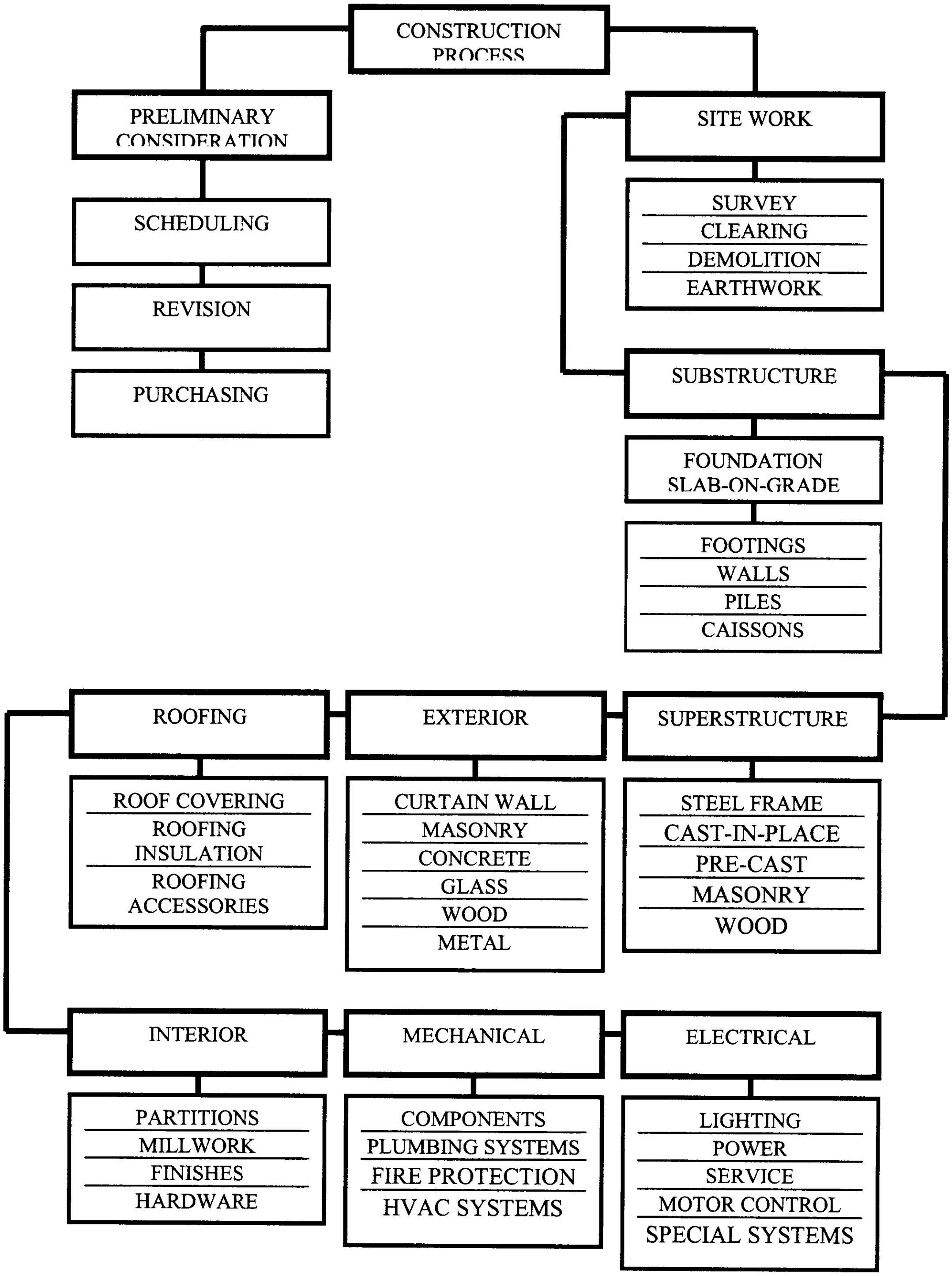

Figure 9 - Conventional construction process - *Fundamentals of Building Construction - Edward Allen*

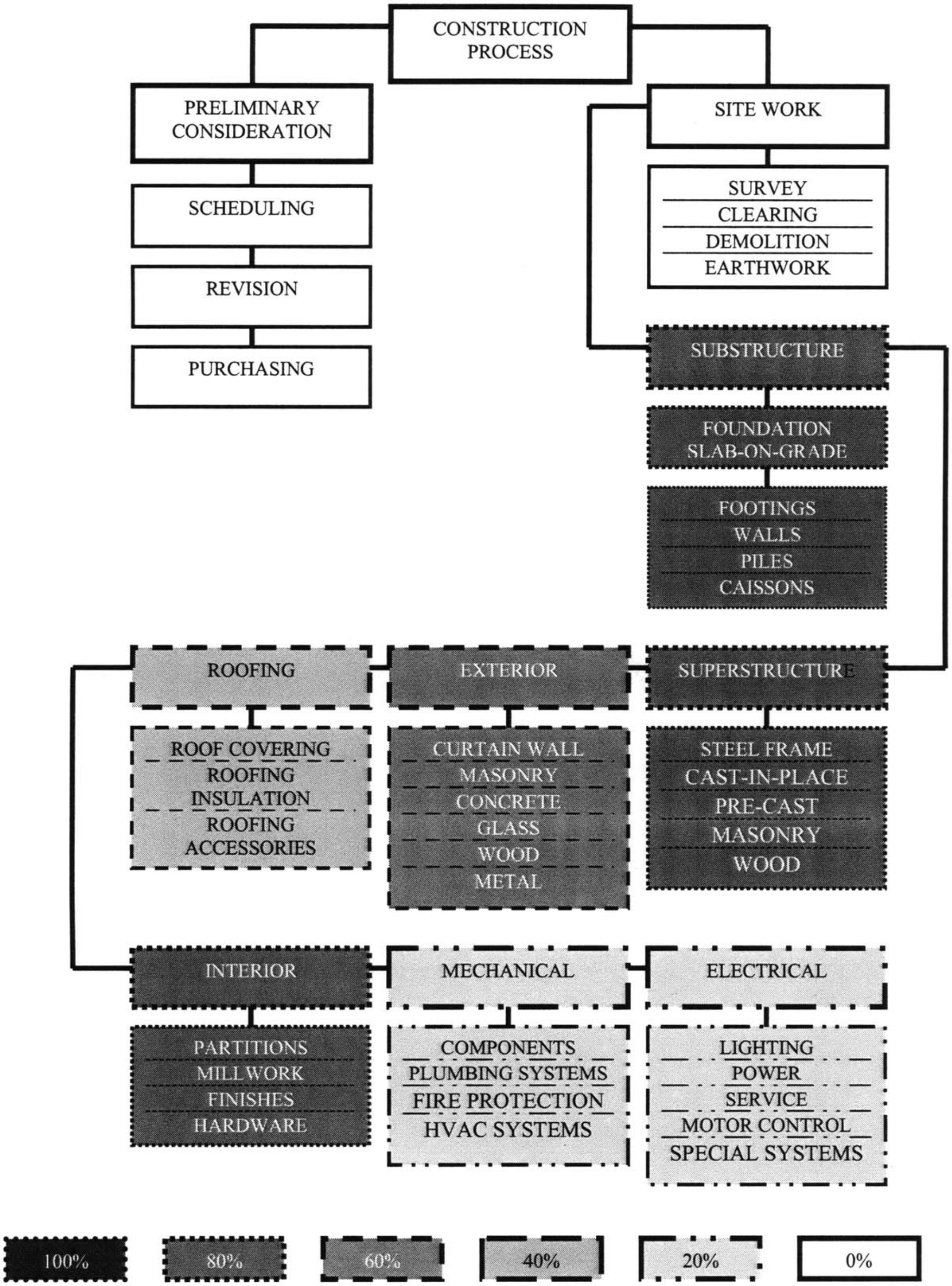

Figure 10 - Percentage of construction tasks that currently have or being considered for automated technology by either as components within an overall automated construction system or designed to do the specific-task such as individualized robots

CHAPTER 2:
AUTOMATION IN THE 20TH CENTURY

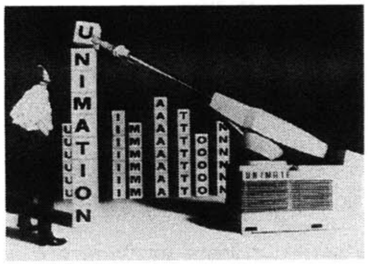
Figure 11 - Unimate assembly robot - *Fabian Winkler - ETB, School of Art, Carnegie Mellon University*

In 1954, George C. Devol patented a technology called 'universal automation', which eventually became the foundation of a corporation called Unimation. At the time, Unimation was known as the world's largest maker of industrial robots. It went on to produce early hand built machines called Unimates and sold its first robot, serving a die casting machine, to the Ford Motor Corporation in 1961[4].

Originally, Unimation and its competitors intended for these automated machines to be replacements for repetitive and tedious production tasks such as tending to various casting, molding, cutting and pressing machines. Their focus was on

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[4] For more information on the birth of industrial robotics and Unimation, please refer to the special issue of *Industrial Robot Magazine* called Decade of Robotics. Special Tenth Anniversary Issue of the Industrial Robot Magazine. IFS Publications. 1983.

machines that create and manipulate existing parts as supposed to inventing new tools.

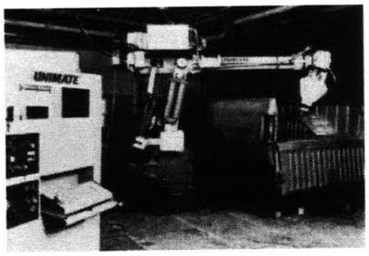

Figure 12 - Unimate painting robot - *ETB, School of Art, Carnegie Mellon University*

However, that strategy would later change in 1964 when Ole Molaug, an engineer at a Norwegian agricultural company, needed a solution to solve their problematic job of painting wheelbarrows. With automated technology rising in popularity, he invented a very simple automatic painting machine. Unlike the intention of the Unimates, Molaug's painting machine was created for the purpose of providing a solution to a problem.

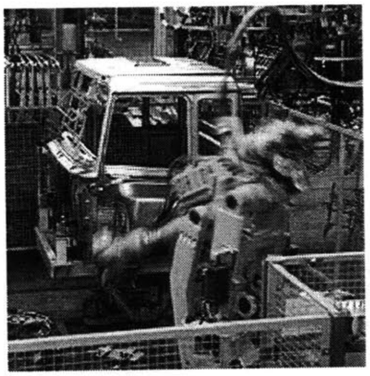

Figure 13 - Factory automation robot - *Jay Tracy Associates*

Automated painting was then quickly followed by automated spot welding. When the automotive industry realized the potential in automated spot welding, the productiveness within the automotive assembly as well as other manufacturing industries increased dramatically. Requests for spot welding robots came pouring in and Unimates, which were already being produced, became the ideal design model for this particular type of task. Unimation altered the Unimates for spot welding duties and took complete control within the industry for the production of specialized spot welding robots from this point onward.

By the 1970's, the industry's acceptance and enthusiasm for automated technology and industrial robots grew larger as similar occurrences began to appear. Other countries around the world also began to take notice. A spectator at the time and in dire need of an economic boost, Japan completely embraced this technology like no other country. Since that time, Japan has been the world wide leader in the field of automated industrial robots. Currently employing 45% of the industrial robots worldwide, Japan is ranked the number one user and producer of automated industrial robots. The United States and Germany are second and third respectively with 15% and 13%[5].

Figure 14 - Typical assembly robot - *ABB Industrial Robotics Company, Japan*

In 1971, Japan became the first country to adopt a robot association, which was known as the Japanese Industrial Robot Association (JIRA). In 1975, the Robot Institute of America (RIA) was formed in the United States and Britain followed with BRA or also known as the British Robot Association. Since then, countries all over the world have adopted similar organizations and associations.

2.1 Introduction to Automation in Construction

The exact origin of automated construction is somewhat vague. However, with the advancement of industrial automation in the early 1980's and the boost in the economics of automated manufacturing, engineers in the construction industry quickly saw the possibility and became captivated with the concept of automated construction. Companies as well as research institutions worldwide began to design, test and develop this new technology.

However, by the early 1990's, this new trend began to dissolve. Researchers and engineers started to realize that there were several complications. The costs of implementing autonomous construction techniques were becoming too high and although supporting technologies existed, the majority of the technological advancements necessary for the successful execution of construction methods had not yet been invented. The complexity of automating the simplest task was overwhelming and as the solutions to these technical challenges

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[5] Data was provided by Dr. Junichiro Maeda during a presentation at Shimizu Corporation, Japan on April 26, 2005.

seemed unfeasible, the interest of automated construction faded away.

Nevertheless, the ideology and methods of the automated construction process affirm that there are logical and economic gains worth considering. When compared to the traditional process, the automated process is considerably more effective in almost every significant category. Take for example the reduction of man-hour for every one-floor cycle. The contrast between the two processes shows that automated processes can reduce human labor by roughly 50% compared to the traditional process.

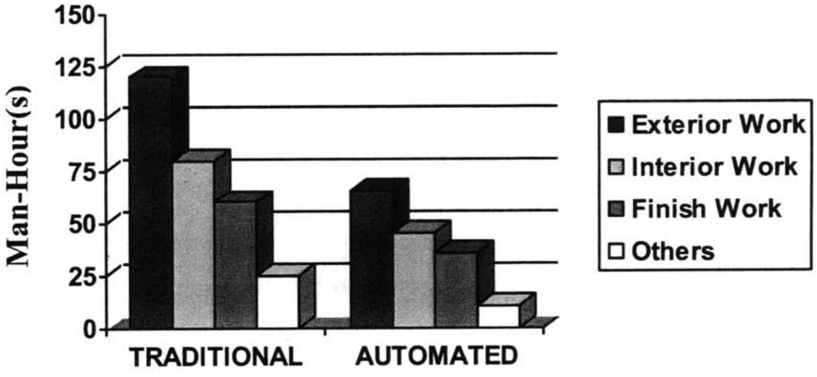

Figure 15 - Reduction of Man-Hour (1 Floor Cycle) - *Source provided by Shimizu Corporation referring to the automated construction system called SMART System.*

Additionally, when compared to the overall reduction of man-hours within the entire construction process, the automated process in fact reduces human labor by 30% compared to the conventional method.

The category of exterior work alone, which typically involves installation of exterior panels and building facade work, usually takes over half the amount of time of the entire construction period. Yet, with the automated process, it received the most significant reduction in the total amount of construction days. The reduction ranges anywhere between 55% and 65% percent less than the traditional process.

Another example of the advantages that the automated process has is the reduction of construction waste. By using wide arrangements of pre-fabricated materials with modular and systematic application methods, therefore, minimizing on-site cutting and almost no individualized packing of materials and parts, the automated system has the capability of reducing construction waste by 50%.

However, the prime factor that exemplifies the benefit of using the automated construction process over the traditional process is the shortening of the construction time. Although the initial set-up of the automated process takes longer than the traditional process, once the system is set up, as the number of floors increases, the process can actually become more productive. Therefore, when calculating the number of days per floor for the entire construction period, such as for a typical 20-story building, the automated process shows on average a 15% reduction in construction time.

For example, if a floor takes 7 days to construct with the traditional process, the automated process can produce the same floor in 5.5 days. The figure below (Figure 13) describes the length of the construction period for a 20-story building using Shimizu's SMART automated construction system in comparison with the traditional process. Even though not all automated construction system produce the same conclusive result, overall, the automated process has the potential to outperform the traditional process in every significant category.

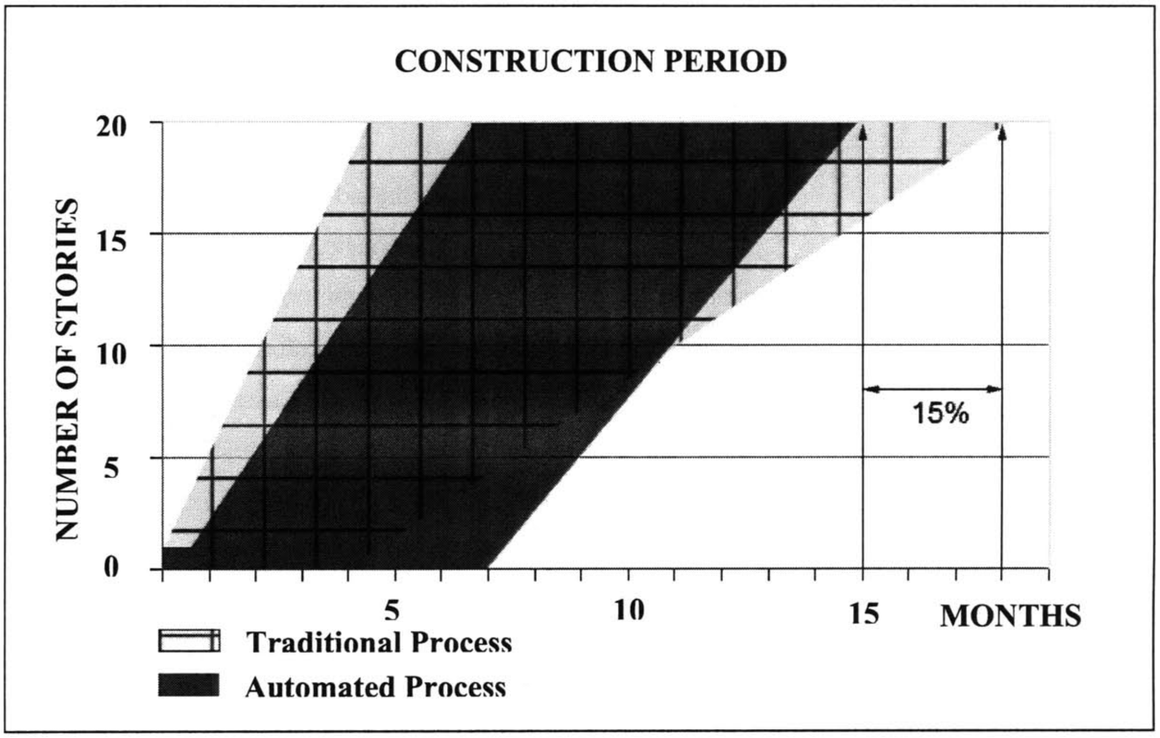

Figure 16 - Construction Period - Data provided by Shimizu Corporation describing the SMART System

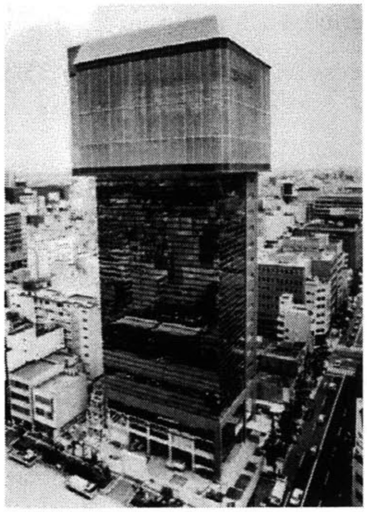

Figure 17 - SMART building system - *Shimizu Corporation, Japan*

2.2 Construction Automation in Japan

Since the 1980's, developments of automated construction technologies in Japan have been steadily increasing. However, during a recent visit to Japan's leading automated construction companies, new impressions of the current development of automated construction were gathered. These revelations were not necessarily surprising, but nevertheless, unexpected. For being the current world leader in the advancement of automated technology, Japan's current progress in the area of construction automation is rather lethargic. Overall, Japan's construction industry continues to be a labor-intensive industry with minimal usage of automated technologies.

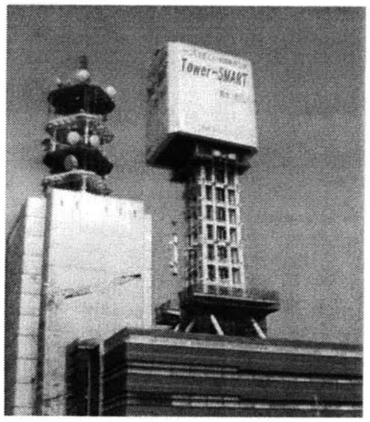

Figure 18 - Tower-SMART building system - Shimizu Corporation, Japan

Since the construction boom of the early 1990's, Japan's leading construction companies have been pushing to discover ways to increase productivity, efficiency and safety within the working environments. Realizing that automation is the answer, they have been investing millions of dollars in automated construction research. Although several buildings have been built using advance automated techniques, however, desirable implementations of this type of technology are still many years away.

One major factor in the slow acceptance of this method is cost. Even though these automated buildings were constructed in record time, conversely, the cost to operate and control the entire system is way beyond the acceptable amount. Until advances in automated technology are realized, the traditional manual process will always be superior over the automated process.

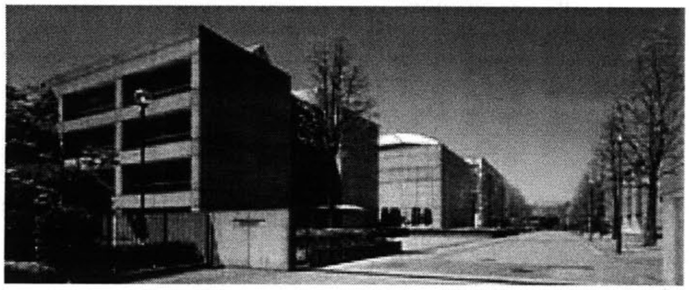

Figure 19 - Kajima Technical Research Institute - *Tobitakyu, Chofu, Tokyo, Japan*

According to the Architectural Institute of Japan (AIJ), over 150 different types of construction robots have been developed for the purpose of automating the construction site. However, the majority of these robots have never been used on the actual construction site and several technological issues remain to be resolved. Consequently, a long-term developmental approach has been established by the Robotics Committee of the Architectural Institute of Japan and Japan Society of Civil Engineers for future research and development. Over 30 major construction corporations have accepted this plan and at one point or another proposed, developed and examined possible applications of robotics technology for construction operations. Of the 30

Figure 20 - Shimizu Corporation Institute of Technology - *Shimizu Corporation, Japan*

corporations, that include companies such as Kajima Corporation, Komatsu Ltd., Taisei Corporation, Takenaka Corporation, Tokyu Construction Co., Ltd., and many others, notably Shimizu Corporation and Obayashi Corporation are currently the most active companies. In addition, since the mid-1980, these two corporations have developed the most automated construction robots and systems to date.

2.2.1 Shimizu Corporation

Considered to be one of the largest construction companies in Japan, Shimizu Corporation directs a field of engineers at the Institute of Technology in developing various automated construction technologies. Active since the mid-1980, the Institute of Technology at Shimizu Corporation has been conducting various forms of research in automated technology with the aim of developing specialized automated building systems and robots that can be assigned to complete specific tasks.

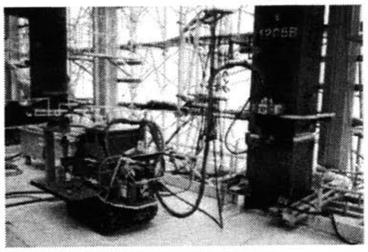

Figure 21 - Spot welding robot - *Shimizu Corporation, Japan*

The results from the research and development gave birth to the SMART (Shimizu Manufacturing system by Advanced Robotics Technology) system and several task-specific construction robots concentrating in the areas of exterior and interior construction works, as well as the inspection and maintenance of the incomplete and completed construction site. With the objectives of relieving workers from the many dangerous construction operations, providing consistently high quality products, and making the working environment a safer place, Shimizu Corporation designed these specialized robots and systems in order to regulate the number of industrial accidents and to improve construction productivity. However, the expected results from these improvements have yet to be fulfilled. Nevertheless, Shimizu and other major construction corporations are continuing to apply significant advancement to the research and development effort for the betterment of the entire construction industry, in hoping someday in the near future, to be able to achieve the desired results.

2.2.2 Obayashi Corporation

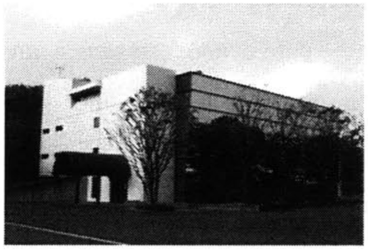

Figure 22 - Obayashi Technical Research Institute - *Obayashi Corporation, Kiyose, Japan*

Riding alongside Shimizu's Institute of Technology is Obayashi's Technical Research Institute (TRI). The TRI has been conducting similar types of research in the area of automation technology. With parallel objectives of reducing construction time and total cost, increasing safety, and enhancing the working conditions and surrounding environments, Obayashi's TRI took on the concept of developing an overall automated construction system that replicates a factory environment.

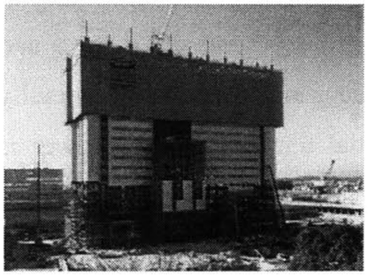

Figure 23 - Automated Building Construction System (ABCS) - *Obayashi, Japan*

Started in the late 1980's and early 1990's, developments of fully automated building construction system looked to combine the latest management control information technology with a variety of construction robots to form a fully-controlled automated construction environment. With the development of Automated Building Construction System (ABCS), Obayashi's TRI has been in the forefront of research and development in this area to refine and perfect the overall automated building systems.

With a total of 8 different corporations developing and introducing over 12 overall building systems on more than 20 construction sites thus far, the limitations and possibilities of this type of development have barely scratch the surface[6].

2.3 Conventional versus Automation

Figure 24 - Interior view of SMART system - *Shimizu Corporation, Japan*

The automated construction system has several advantages over the traditional process. It not only gives the workers a protective weather-free working condition, but also allows for a safer and more productive working environment. An increase in prefabricated and unitized production techniques provides a never-seen-before level of efficiency for the construction site. Improving productivity has always been one of the primary goals for automated technology and with a system that introduces simplified on-site conveyance systems and systematic assembly work, such as the ABCS, the ideal proficient construction site is slowly becoming a reality. However, cost remains and will constantly be the focal point in the effective utilization of automated techniques.

How It Compares

With automation, the entire traditional construction process is altered. Traditionally, during the construction phase, the sub-contractors are involved sequentially, the scheduling of materials, equipment, and production is critical, precise and detail oriented planning of manufacturing assembly are carefully considered and lastly, a substantial amount of man power is being utilize.

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[6] For more information on the complete list of the overall automated construction systems methods and their descriptions, please refer to the June 1997 issue of Construction Robot System Catalog in Japan published by the Council for Construction Robot Research.

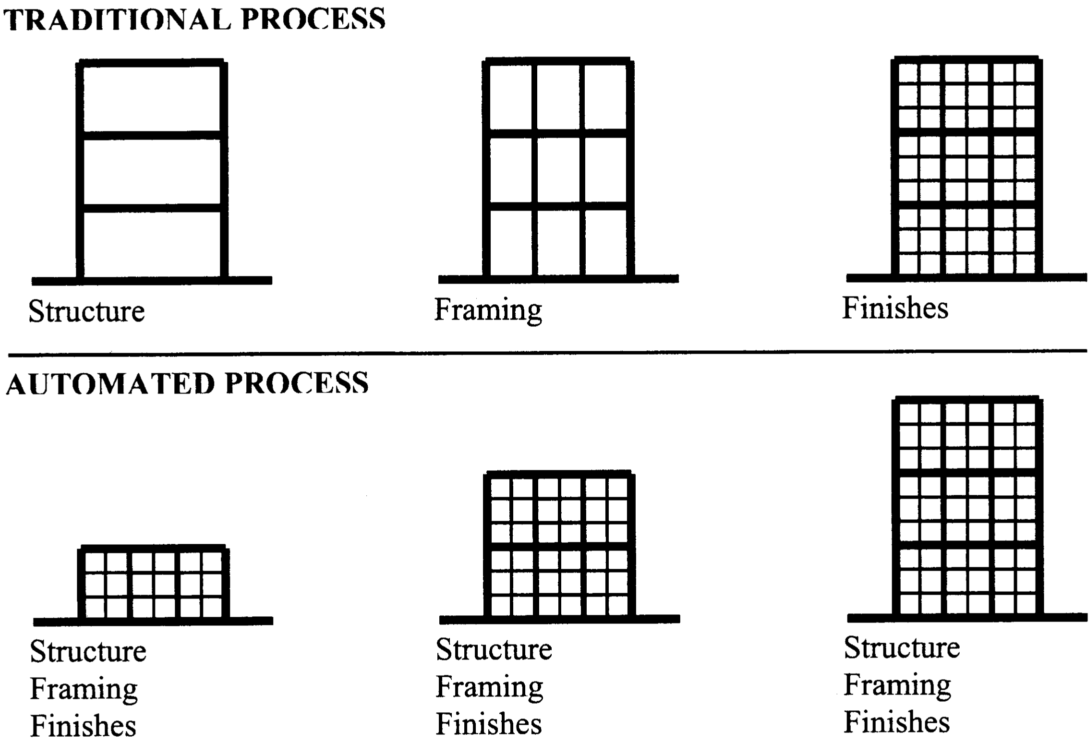

Figure 25 - Traditional process versus automated process utilizing the automated building systems

On the other hand, the automation technology completely contrasts the procedures aforementioned. In the automated process, sub-contractors are involved simultaneously doing parallel progress. The delivery process of materials and equipment are much faster with just-in-time coordination. Additionally, with applications that utilizes systematic assembly; the site is further controlled and simplified. And finally, with the reduction of man-hour and the overall construction period, less man power are required to work long and strenuous shifts.

Systematic assembly is perhaps the most notable feature of the automated construction system. It requires the system to extensively utilize prefabricated and unitized products. Modularity and universal connections can offer not only precise and rapid productivity, but also minimize field labor and above all, effectively reduce the overall cost.

With the automated process, construction tasks are no longer linear. Rather, they are employed as a cohesive unit working simultaneously to construct floor by floor. Floor-to-floor construction requires that each floor has to be completely done in order to move on to the next, therefore, materials and equipment, that are normally being fabricated and installed successively, are now required to be prepared and ready for installation at the same time[7].

The primary reason that these automated systems and specific tasks robots are costly is that they were designed to be too specific. These robots and systems are expensive to develop and once produced, they can only serve for that particular purpose.

However, if there was development of a robot or a system that has the ability to carry out multiple duties and at the same time, be intelligent enough to adapt to various problematic scenarios, the desire to have them would be in much higher demand. Therefore, the development of a multi-purpose construction robot might be the key to push forward the industry-wide acceptability of automation in construction.

2.4 Progress in Automated Building Technology

In the last few years, there have been drastic advancements to make automated construction systems and robots more cost effective. The automated construction technology has been steadily improving through a series of

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[7] This is referring to the house "chassis" - a standard intelligent panel connection system that is currently being developed by Changing Places and House_n consortium as a research project for the Media Laboratory at MIT.
- For more information on this subject, please refer to Changing Places and House_n website at http://architecture.mit.edu/house_n/

technical and design modification, simplification and reduction in the level of necessary automated tasks. A good example of this steady improvement is the ABCS by Obayashi. Over the course of its development, the ABCS have been introduced into four different sites with each site having a unique goal and application strategy. With each revolving project, the ABCS showed vast improvements in every notable category.

To further the understanding of the current state of automated technology, a detailed investigation of these systems and robots is required. In the following chapter, examinations and analyses of existing automated technologies are discussed. Although some of the developments described in this chapter are developments of the past and have long been terminated, there are still a wide range of robots and systems that are currently being modified and are being improved by numerous major construction corporations today.

2.4.1 Automated Building Construction System (ABCS) for High-rise steel structure buildings (Orig. 1989) (Ikeda and Harada, 2004)

Since the 1980s, Obayashi Corporation in Tokyo, Japan has been exploring the field of automated building construction technology with the objectives of shortening the construction time, reducing total cost and rejection, improving productivity and quality, increasing safety, and enhancing the local working conditions as well as the surrounding environments.

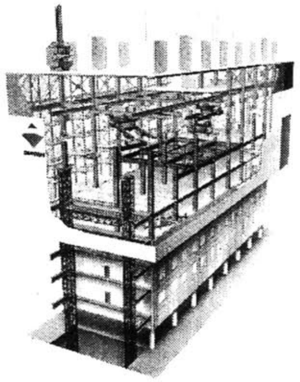

Figure 26 - Automated Building Construction System (ABCS) - *Obayashi Corporation, Japan*

Developed for constructing high-rise steel structure buildings, the Automated Building Construction System (ABCS) introduces the concept of factory automation to the construction site and allows the majority of the on-site work to be done in a factory-like environment. The ABCS takes on automation, robotics, and computer technology to employ tasks for building construction. The ABCS integrates the Super Construction Factory (SCF), which provides an enclosed all-weather facility, with automated tools, equipment and a centralized computer control system.

Traditionally, building high-rise steel structures usually requires working with tower cranes, therefore, their effectiveness, quality and progress of the work largely depends on the weather conditions. In addition, working at such elevated conditions is not only hazardous for the workers but also bears many complications for the equipments.

In 1989, the ABCS was developed to solve these issues as well as to increase productivity. The ABCS uses an erection system for installing steel members, external panels, etc. which differs from a typical conventional tower crane system, all within an enclosed space to protect the working environments from the elements.

CONFIGURATION

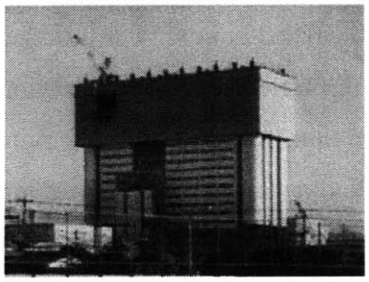

Figure 27 - Exterior view of the Automated Building Construction System (ABCS) - *Obayashi Corporation, Japan*

The main components of the ABCS are comprised of an enclosed structure serving as a working envelope, a parallel delivery system (PDS) and an integrated management system that also includes three subsystems: the production management system, the equipment operation management system and the machine control system.

The enclosing structure of the working space also can be referred to as Super Construction Factory (SCF), which includes a roof and surrounding walls and is supported by steel columns erected on top of the building frame. The support columns (climbing supports) that penetrate the SCF frame are erected on top of the building's steel columns and at the highest part of each column the climbing equipment is attached. Each component of the climbing equipment is controlled centrally by an operator through the use of two hydraulic jacks.

The PDS consists of high vertical hoist ways for lifting materials and overhead traveling cranes, all acting as vertical and horizontal transportation methods serving the entire construction floors of the building. There are two types of the SCF cranes and they are set below the roof. One consists of a rotating arm and has a lifting capacity of 13 tons; the other crane's beam slides laterally and has a lifting capacity of 7.5 tons.

On a typical construction floor, the SCF cranes carry out all of the horizontal movements which include installation of steel columns and beams, pre-cast concrete floor slabs, and external paneling on the side walls of the building. Remotely controlled special holding devices are required to assemble the steel columns and beams for lifting, and as well as dismantling. The material lift is used to haul up various working and finishing materials along with tools and equipments, etc., from floor to floor.

PROCESS

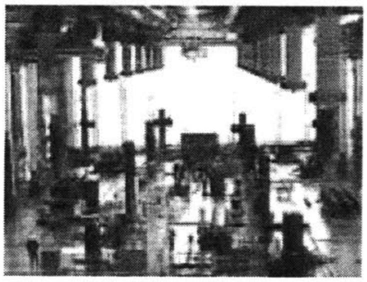

Figure 28 - Interior of a Typical Floor Construction - *Obayashi Corporation, Japan*

The first stage requires the SCF to be assembled manually and then the PDS is installed. Second, inside the SCF, the typical floors are constructed one by one. Then, at the final stage, the SCF's main structure is first lowered to join together as part of the building structure and then all the temporary parts of the SCF are dismantled. For the typical floor construction (TFC), regardless of the weather conditions, the building frame and exterior work can be carried out inside the SCF.

When the TFC of one floor is completed, the climbing equipment built into the support columns raise the SCF up to the next level. Then the TFC process is repeated for that floor.

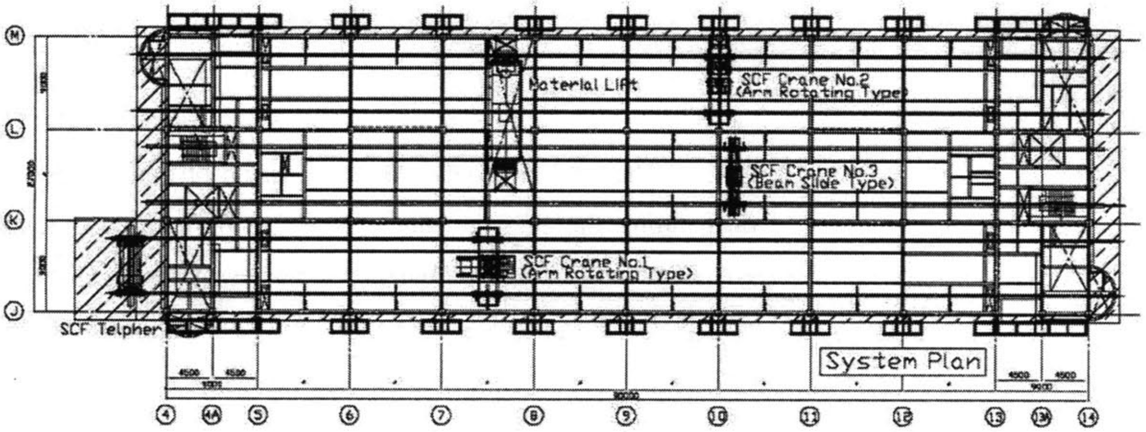

Figure 29 - Typical Super Construction Factory (SCF) plan - *Obayashi Corporation, Japan*

APPLICATIONS

Three years after the ABCS was announced to the press, it was applied four times over a period of ten years. The first and second projects (Project S and N1) began in 1992 and 1995, respectively, and were essentially used as development stages for the system with the main purpose of quality control. The third project (Project J) which began in late 1999 looked to simplify the system for shorter construction period and was prioritized for working with steel structures. In 2002, the fourth project (Project N2) focused on the optimization of the entire system as well as dealing with the issues of lowering the cost and re-using materials from the first project.

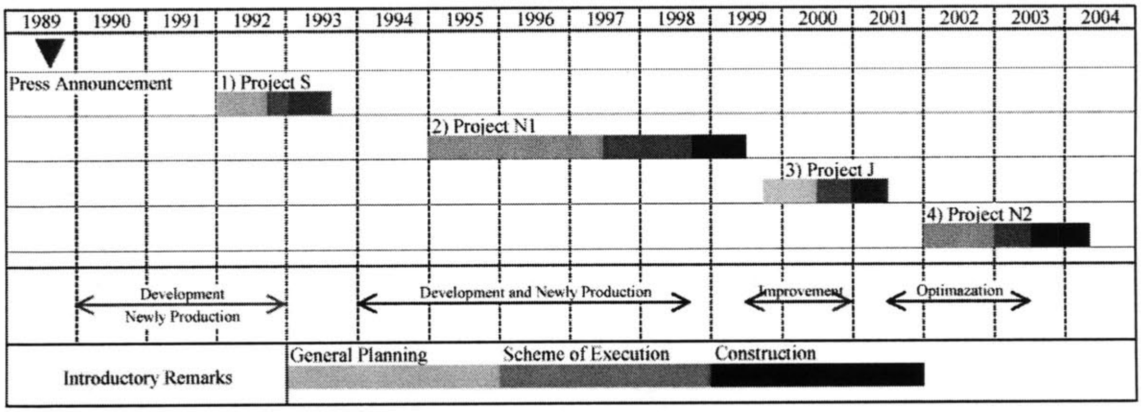

Figure 30 - Graph of the 4 applications - *Obayashi Corporation, Japan*

The total ABCS construction period of assembling and dismantling the SCF is longer than that of traditional tower cranes method. However, during the stages of the TFC by the ABCS, the steel work and the exterior finishing work can be done simultaneously, so the combined working period of the TFC by the ABCS is actually shorter than the conventional method. The ABCS method shortens the construction period effectively as the number of typical floors increases.

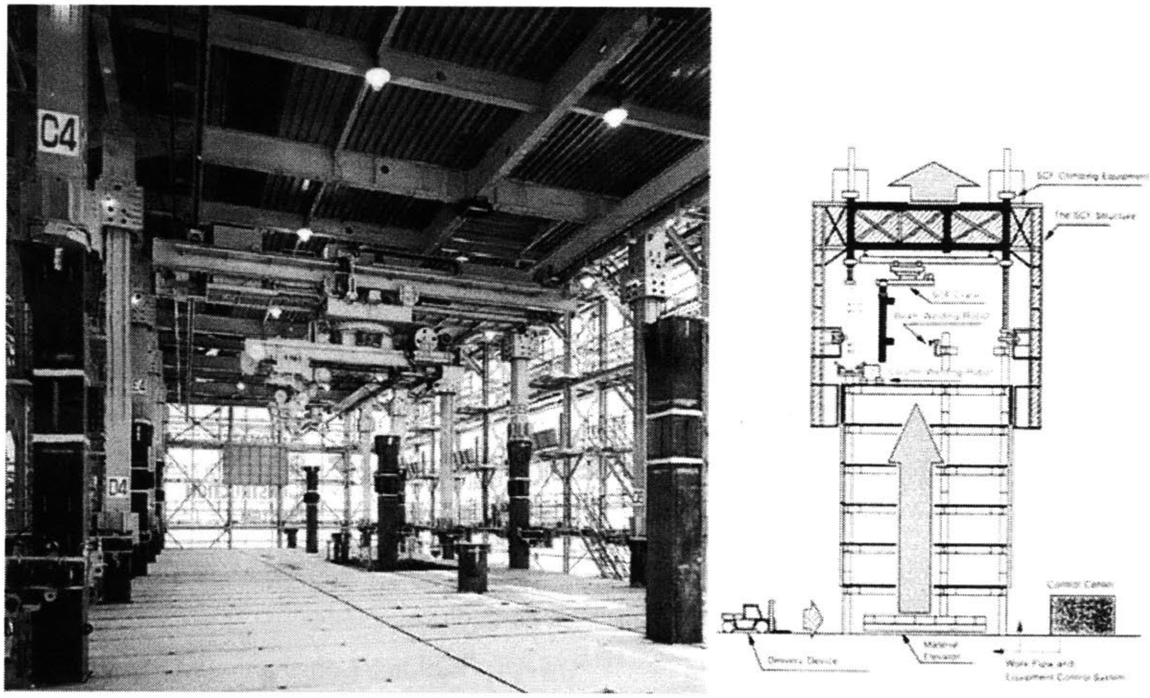

Figure 31 - Interior view and section of a Typical Floor Construction (TFC) - Obayashi Corporation, Japan

Throughout the four projects, there were significant signs of improvement in productivity, quality, and working conditions as well as reducing the safety risks of the surrounding environments. In each project, the construction results were analyzed in detail, and then registered back to system for planning of the next project. As a result, the ABCS construction period and labor time in each project were drastically reduced.

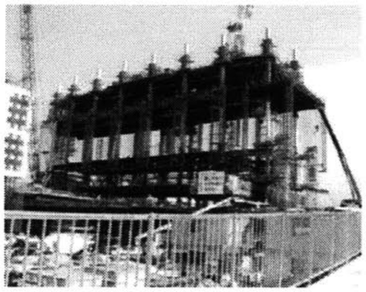

Figure 32 - Construction of Project J - *Obayashi Corporation, Japan*

However, there is still a need to further expand the flexibility of each application, along with developing more simplified technologies for future uses. As mentioned earlier, there are approximately 12 unique automated construction building systems that had been proposed or are currently being developed in Japan. The following is a partial list that includes the companies and the names of the automated construction systems that are currently in development:

- Fujita Corporation
  - Automated Weather-Unaffected Building Construction System (AKATSUKI 21)
- Kajima Corporation
  - Automated Building Construction System (AMURAD Construction System)
- Obayashi Corporation
  - Automated Construction System for Reinforced Concrete Building (BigCanopy)
- Shimizu Corporation
  - Computer Integrated and Automated Construction System (SMART System)
- Taisei Corporation
  - "T-UP" Building Construction Method
- Takenaka Corporation
  - Roof Push Up Construction Method

Note: For more information on these systems or methods and their descriptions as well as a detailed analysis of the ABCS, please refer to the June 1997 issue of Construction Robot System Catalog in Japan published by the Council for Construction Robot Research.

2.4.2 Contour Crafting (CC)

(Orig. 2001) (Khoshnevis, 2004)

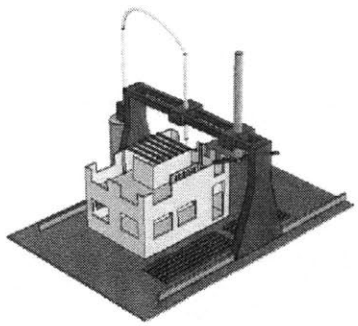

Figure 33 - Construction of conventional buildings using Contour Crafting - *Dr. Behrokh Khoshnevis, USC*

Designed to advance the technology of automated construction techniques in a quest to construct large scale structures with internal features, Contour Crafting (CC) developed by Dr. Behrokh Khoshnevis at the University of Southern California in the department of Industrial & Systems Engineering, utilizes the great potential of automated construction of whole structures as well as sub-components through the uses of recent layered fabrication technology.

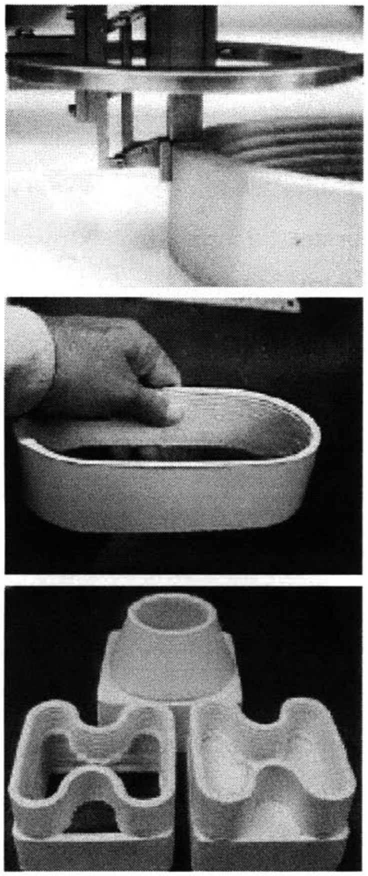

Figure 34 - Troweling techniques of Contour Crafting - *Dr. Behrokh Khoshnevis, USC*

Similar to other fabrication techniques such as 3D printing, Contour Crafting (CC) is an additive process that uses computer control technology to exploit the superior surface-forming capability through the use of a simple manual process known as "troweling". One of the main components of CC is the use of two trowels, which act as two solid planar surfaces, creating exceptionally smooth and accurate surfaces on the object that are being fabricated. This gives CC an advantage when compared with other layered fabrication processes. For instance, a better surface quality, higher fabrication speed, and a wider choice of materials can be achieved.

The versatility and effectiveness of the trowels acting as blades for contouring complex free-form as well as planar surfaces is evidenced by ancient ceramic art works that are often contain intricate or complex surface geometries in addition to detailed plaster work that has shapes as elaborate as flowers. Today, surface shaping knives are widely used in industrial design process such as carving clay models for automotive prototypes.

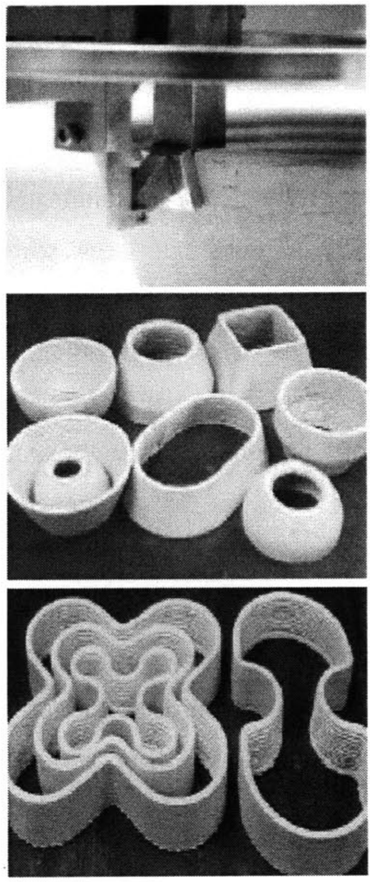

Figure 35 - Shapes created by the troweling techniques of Contour Crafting - *Dr. Behrokh Khoshnevis, USC*

Despite the advancement in computer numerical control mechanization and robotics, the progression of using these simple but yet very powerful tools is still a manual process, and is very limited.

On the other hand, CC takes advantage of troweling through the uses of computer control superior surface forming capability to create smooth and accurate, planar as well as free-form surfaces. Moreover, the layering technique allows for the creation of various surface shapes using less unique troweling tools than that of traditional plaster handwork and sculpting.

CC combines the process of extrusions and filling for forming the object surfaces and pouring or injecting to make the object's core. When the material is extruded, the trowels follow the nozzle to create smooth outer and top surfaces of each layer. If required, the planar trowel can be adjusted to various angles in order to create non-orthogonal surfaces. During the extrusion process, it is necessary to only build the perimeter edges (rims) of each layer of the object. Once the extrusion of each closed section of a given layer is completed, filler material can be filled between the areas defined by the outer rims if necessary.

BUILDING CONSTRUCTION

The CC application in building construction requires a gantry system carrying the nozzle that moves along the two parallel lanes installed at the construction site. In a single run, a house or a series of houses with a different design may be automatically constructed. Conventional structures and the CC system can be integrated with a support beam placement and arm positioning system.

The following are some interesting aspects of this automated construction technology:

Design Flexibility

The CC process allows designers to visualize complex structures with functional and exotic architectural geometries that can be difficult to achieve using the current traditional construction procedures.

Multiple Materials

The CC system also allows for the use of various materials for exterior surfaces as well as filaments. The CC nozzle barrel was designed to mix and feed multiple materials that can chemically react with one another. The deposit amount of each material is controlled by the computer and dispersed to various regions of the object being built. This allows for the construction of structures that contain varying amounts of different compounds in different regions.

Automated Reinforcement

In Figure 15, the images depict a modular embedment of steel mesh reinforcing within each layer of material. There are three simple modular components, each can be fed by an automated feeding system that positions and assembles the parts in between the two outer rims. In addition, a three dimensional mesh may be built for supporting columns using the same system. After the assembly process and the rim walls are erected, concrete may then be poured in between the rims and over the reinforcement. The assembly of the mesh can duplicate the shape of the structure.

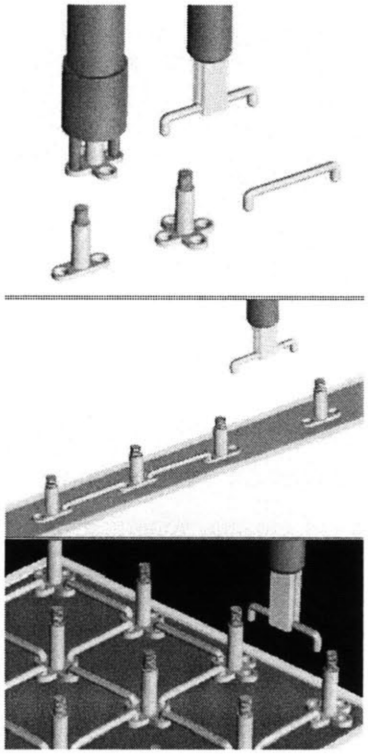

Figure 36 - Reinforcing process by Contour Crafting - *Dr. Behrokh Khoshnevis, USC*

As for an alternative to traditional metal reinforcement, the CC is also designed to use advanced materials such as fiber reinforced plastics (FRP). There is also the discussion of co-extrusion and the possibility of feeding glass or carbon fiber tows through the CC nozzle to form continuous reinforcement consolidated with the deposition of the matrix materials. Also considered is the deposition of the FRP reinforcement by a parallel nozzle built into the CC nozzle assembly.

Automated tiling of floors and walls

This process is designed with two robotic arms installed on the same structure which moves the CC nozzle, one applying adhesive materials to the surface while the other arm locates the tiles and places them over the treated area.

Automated plumbing

Once the fabrication of the wall layers have been achieved, a segment of the plumbing pipe is attached onto the lower segments already installed. In the case of heating pipes, (Figure 16, top) each connection is held together by a heater ring that has been pretreated with a layer of solder either on the inside or the outside of the ring. The ring then heats up to bond the two pipes together. There are also designs for several universal passive (requiring no active opening or closing) robotic grippers (Figure 16, bottom) and heater mechanisms that can be used with various pre-manufactured plumbing components.

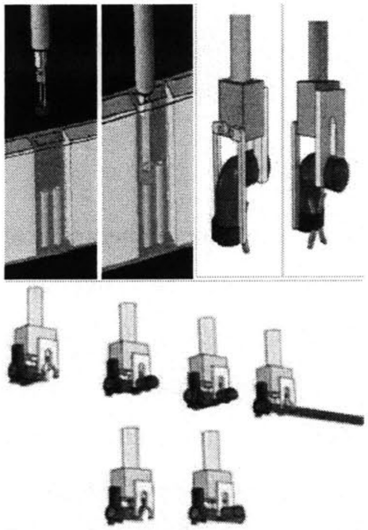

Figure 37 - Automated Plumbing by Contour Crafting - *Dr. Behrokh Khoshnevis, USC*

Other aspects of CC construction technologies that have been taken into considerations are:

Utility Conduits – Which can be built precisely as dictated by the CAD data, into the walls of a building structure.

Paint-Ready Surfaces – Additives such as sand, gravel, reinforcement fiber, and other applicable materials available locally may be mixed and extruded through the CC nozzle.

Smart Materials – The accuracy control of the amounts of selected smart construction materials, such as smart concrete, may be deposited precisely in the intended locations.

Automated electrical and communication line wiring – Modules of power and communication lines embedded in electrically conductive and non-conductive materials such as a polymer, and connect modularly, similar to the process of installing plumbing. Likewise, all modules are capable of being fed and connected robotically.

Automated painting – A sprayed painting mechanism can be attached to the CC main structure to perform the necessary painting or coating requirements. This painting mechanism can either be a spray nozzle, or an inkjet printer head (such as those used for printing large billboards) serve as an attachment that can be placed directly on the nozzle.

As several statistics have shown, the construction industry accounts for a significant amount of solid waste as well as various harmful emissions and construction activities which generate an exorbitant amount of energy. Typically, the construction of a single-family home generates approximately 3 to 7 tons of waste (City of Austin, 2002). More than 40% of all raw materials used globally are consumed in the construction industry (Lenssen and Roodman, 1995).

CC's technology is electrically powered; therefore, it is entirely emission free. Due to its accuracy in the additive process, Contour Crafting could very well result in little or no material waste. In addition, Contour Crafting has the potential for immediate application in low income housing and emergency shelter construction.

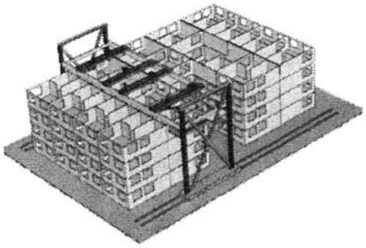

Figure 38 - Contour Crafting multi-level structures - *Dr. Behrokh Khoshnevis, USC*

Ultimately, the CC method is capable of completing the construction of an entire house in a matter of few hours (e.g., less than two days for a 200 m2 two story building) instead of several months as compared to the traditional process. This speed of operation results in efficiency of construction logistics and management and hence favorably impacts environmental concerns.

Note: Full details and more descriptions of Contour Crafting and its methods can be found on Dr. Behrokh Khoshnevis website at http://www.contourcrafting.org/

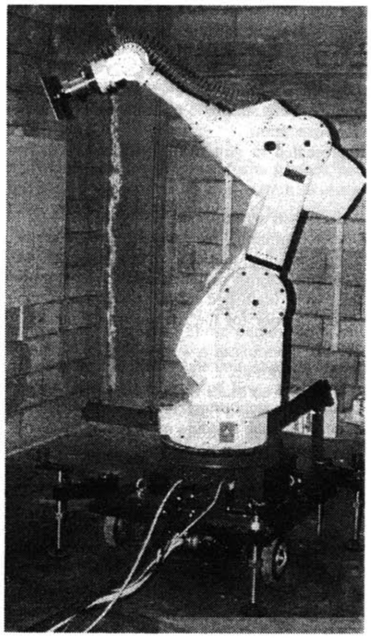

Figure 39 - Large Scale Experimental Robot - *Shimizu Corporation, Japan*

2.4.3 Robot for Interior-Finishing Works (Warszawski, 1991)

In a research paper by A. Warszawski that entails descriptions and strategies for interior-finishing robots, it specifically addresses two significant issues: 1) looking at an overview for the development process of the interior-finishing robot and 2) analyzing the methodology and results of the development stages which involves the selection of the typical configuration for the robot's arm.

The development process includes studies of the different formulations in the specification of the robot's performance, preliminary design stages, planning of several building activities for the robots, analysis of their configurations, adapting the building's technology to the robot's limitations, and examining the robot's physical performance with specific building tasks.

The robotic arm's configuration stages addresses several selection analyses that involves variables such as joint configuration, arm span lengths, links sizes, and the maximum velocity obtained by the joints. Other criteria refer to the overall operation efficiency, productivity, and generating costs.

There are four generic types of the building robot's classification:

1. Robots for assembling large components (e.g., beams, columns, slabs, and exterior walls, which usually constitute the shell of the building).
2. Robots for finishing large vertical surfaces, mainly building facades.

3. Robots for finishing large horizontal surfaces, mainly building floors.
4. Robots for the execution of various interior-finishing tasks after the building shell have been erected.

In Warszawski's paper, the initial designation of these interior-finishing robots were to perform various duties complimenting the prefabricated outer shell of a building such as the envelope, primary and secondary supports as well as floors. The works can also include connecting various fabricated parts, erecting walls, hooking up electrical wiring, attaching mechanical pipes, along with finishing tasks such as tiling and painting.

A major, unique difference between these particular robots and their traditional factory counterparts is that they have the mobility that allows them to move from one spot to another as the works are being completed, scheme the entire work space, and conform to the various working conditions.

There were several key questions that were asked prior to the development of the robots. First, for the on-site duties, should there be only one multi-purpose robot doing all the work or should there be a series of robots performing individual tasks? As the result, individualized robots that are assigned to do a specific task rated much higher in total efficiency with respect to a series of criteria such as degree of freedom, individual payload, and flexibility. Conversely, the results also indicated that in order to be justify economically, these robots were required to work continuously since other support systems such as feeders and effectors were depending on them to maintain a constant work flow.

The second question involves the nature of the robotized work. There were two basic approaches to this question. The first one, much like a construction worker, the robot should be able to move constantly from location to location. And in the second, contrast to the construction worker and similar to a factory robot, static working locations are strategically dispersed throughout the working area limiting the type of work for each robot. In the end, the results depend upon the particular type of tasks being performed whereas smaller tasks would require the mobility factor and larger tasks are situated at a fixed location demanding a static working area.

The other question has do to with configuration, its arm length and the ability to carry payload. Since the work is predicated by the three-dimensional surrounding working area, the sizes of the robots will be determined by the allowable space. In addition, the weight of the robots cannot exceed a certain class so that it is not necessary for the floor area to require additional reinforcement.

The next question deals with the robot's autonomy. On one end, there is a robot that has a sensing capability of a self-guided system such as locating itself at a precise location and identifies the work needed to be done and work through an entire day schedule without any human assistant. On the other hand, the robot works as an extension for a team of workers taking on the physical duties while the workers take on the control and planning strategies.

A description for the flowchart of the development process for interior-finishing robots was realized through several analyses of different performance specifications. It ranges from initial definitions of the specs to preliminary design to testing of physical performance at a small scale (Figure 12) as well as the planning of the robotized work to large scale testing then finally to the development of a prototype.

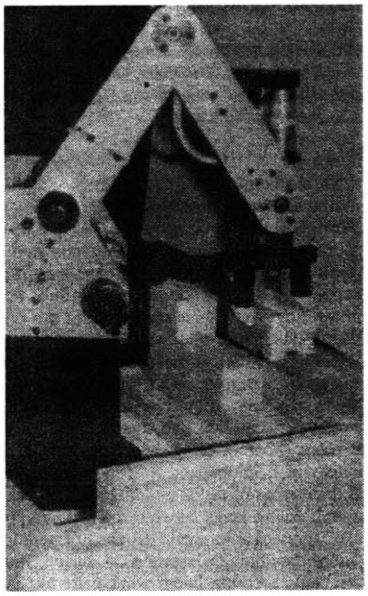

Figure 40 - Small Scale Experimental Robot - *Shimizu Corporation, Japan*

Once the definition is determined, the preliminary design of the machine is established by first identifying representative activities for the majority of the robots. Second, the size of the carriage is predicated by the materials that are required to do the work. Third, height limits are located by the uniqueness of the working space. Fourth, payload is determined and finally, the limit on the weight of the robots is set.

After the preliminary design, come the physical performance requirements for the robots which determine the conditions and operating procedure of the working tools as well as the different ranges in mobility and navigation capabilities.

The next step in the development process is the planning of the robotized work to test the robot's physical performance. This has an important economic factor in the complete usefulness of the robot. A feasibility study done by Warszaski (1985) determined that 50% to 70% capacity is required of each robot in order for it to be classified as economically justifiable. On the performance level, a chart of priorities identifying tasks that are the most time-consuming activities, which in turns receives the highest priority. These tasks includes erection of space dividers, coating applications, applying adhesive to horizontal surfaces such as floors, sealing joints, attaching electrical conduits, and different varieties of connection of the shell elements using adhesive that deals with structural performance.

As a result, multipurpose interior finishing robots offer more flexibility than various individualized robots due to their abilities to modify and adapt to a variety of handling components and control parameters in order to complete a series of finishing tasks. However, development of these robots requires a very intricate analysis of the surrounding environments, testing an assortment of components and their physical capabilities as well as experimenting with specific technologies and evaluating unique economic factors. In the end, the study revealed that the velocity of its arm joints and the cost affect by the life cycle of the robot significantly influence the productivity of the robots.

Note: This section summarizes a research paper that was written by A. Warszawski on the subject of interior finishing robots in the September, 1991 issue of Journal of Construction Engineering and Management, Volume 117, No. 3. For more information on this and many other journals of this type of development, please refer to the wide collections of the Journal of Construction Engineering and Management under the subject of automated construction technology.

2.4.4 Prototype Robotics in Construction Industry

(R. Kangari and T. Yoshida, 1989)

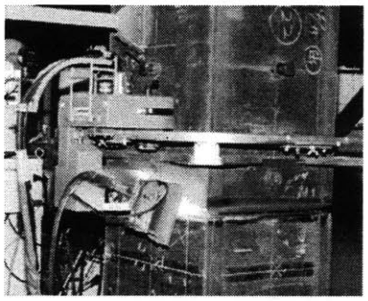

Figure 41 - Automated welding robot - *Shimizu Corporation, Japan*

Shimizu Corporation of Tokyo, Japan started a research and development team in 1975, known in the industry as the Shimizu's Institute of Technology, with the sole purpose of investigating and applying high technology to the dynamic and unstructured world of construction. Its intention was to increase efficiency as well as productivity, improve quality, reduce costs, acquire other markets, and most importantly, improve safety of the construction working environment.

This section addresses several issues such as the increasingly important role that robotics and automation have on the construction industry, as well as examinations of several major construction robots that were in production up until 1989. The primary goal of Shimizu's research and development group was aimed at two specific areas: 1) automation within traditional construction sites and 2) new automated construction applications.

The area of automation research that the R&D team focused on includes *building construction, civil works, nuclear plants, manufacturing facilities, and space development.* Under building construction, specialty robots include several finishing and positioning robots. Within the civil works category, there are cast-in-place substructure systems and auto-drive systems. For nuclear plants, there is the reactor removal system and concrete cutting robot, while in manufacturing facilities, there is the clean automation system robot. Space and lunar-base construction robots fall under the space development area.

Fireproofing Spray Robot (SSR-3)

Designed to diminish the hazardous nature of the spray work for fireproofing steel structural members, the SSR-3 travels and sprays fireproofing material onto structural members along parallel steel beams at a constant distance with the guidance of ultrasonic sensors. It's a numerical control robot that can be remotely operated.

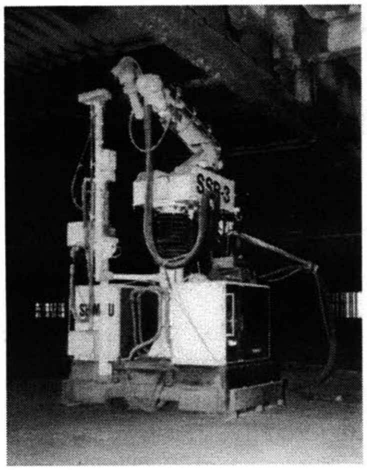

Figure 42 - Components of Fireproofing Spray Robot (SSR-3) - *Shimizu Corporation, Japan*

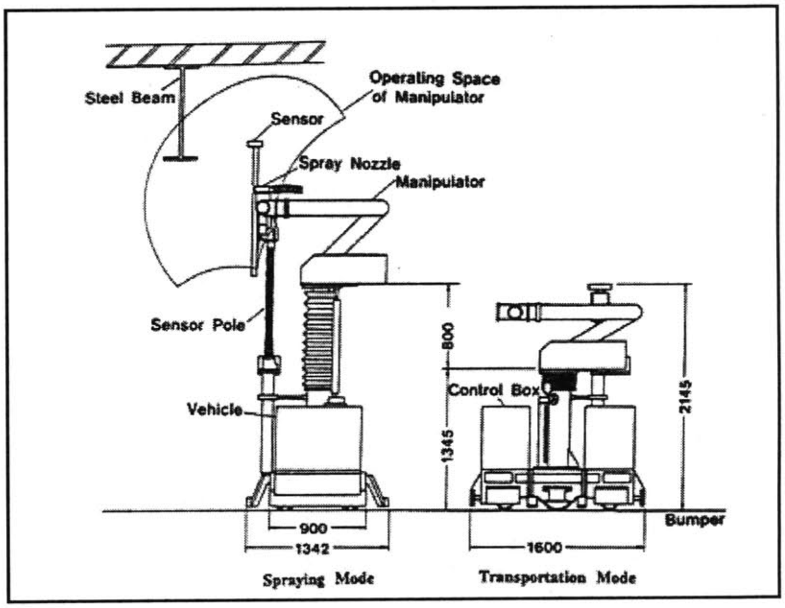

Figure 43 - Components of Fireproofing Spray Robot (SSR-3) - *Shimizu Corporation, Japan*

Steel-Beam Positioning Manipulator (Mighty Jack)

Another dangerous task that can be robotized is steel-beam erection work. With the steel-beam positioning manipulator, two to three steel beams are lifted into the correct position by teleoperation eliminating the need for a tower crane. The Mighty Jack has two grippers, a lifting mechanism, and a hydraulic power unit. The positioning and assembly steps of the manipulator are: 1) position grippers at a desired location, 2) locate the cables on the beams, 3) place the manipulator using a tower crane, 4) situate the manipulator on top of two columns, 5) the cables from the tower crane is released, 6) fine-tune the space

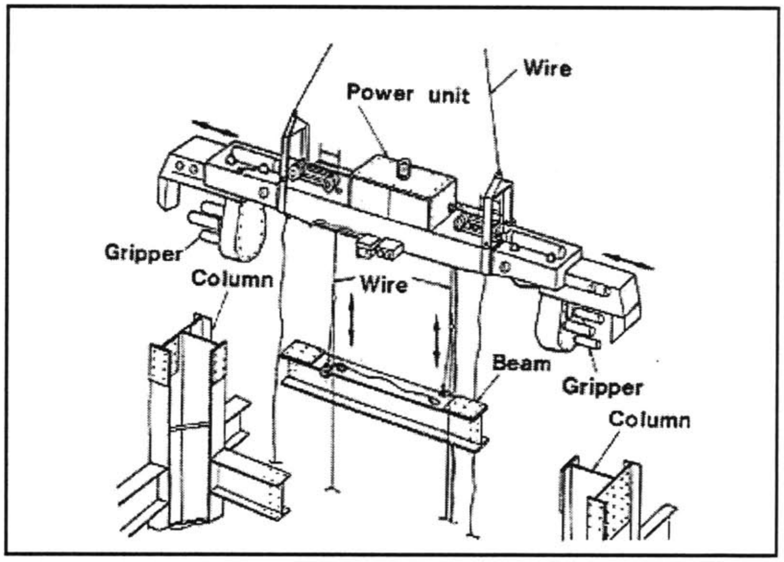

Figure 44 - Components of Mighty Jack - *Shimizu Corporation, Japan*

between the columns, 7) locate the beams one by one in the correct position, 8) join together the columns and beams, and finally 9) raise the manipulator and set it up for the next cycle.

While traditionally, to assemble 6 beams, it usually takes 40 minutes. With the Mighty Jack, the same work takes about 25 minutes. Additionally, a greater deal of efficiency and safety can be accomplished with the Might Jack.

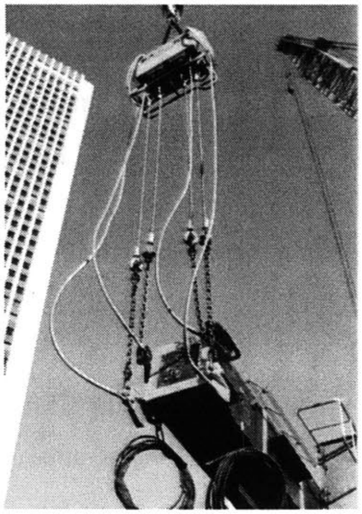

Figure 45 - Components of Mighty Shackle Ace - *Shimizu Corporation, Japan*

Radio-Control Auto-release Clamp (Mighty Shackle Ace)

This clamping tool was developed as a lifting device for steel frame construction work. It consists of a control, a power unit and a lifting tool. The assembly procedure starts with the lifting tool attaching itself to a hole in the column, a worker locks it in place, and then it is lifted up. A crane carries it, and then drops it into position. Once the column is fixed, the lifting tool is unlocked automatically by remote control. Some of the advantages for this system include eliminating the risk of having workers performing these duties at a high altitude; the task can be completed more rapidly then traditional methods; the lifting assemblies are light and can be handled easily by workers; the system is also adaptable to work for assembling curtain walls and units of steels reinforcement; and a locking mechanism that acts as a key safety feature.

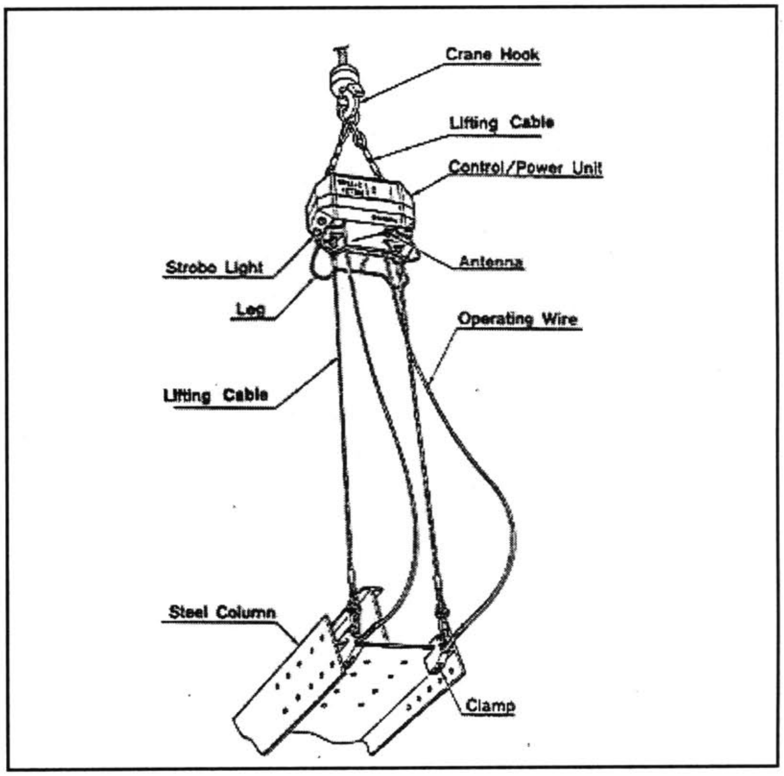

Figure 46 - Components of Mighty Shackle Ace - *Shimizu Corporation, Japan*

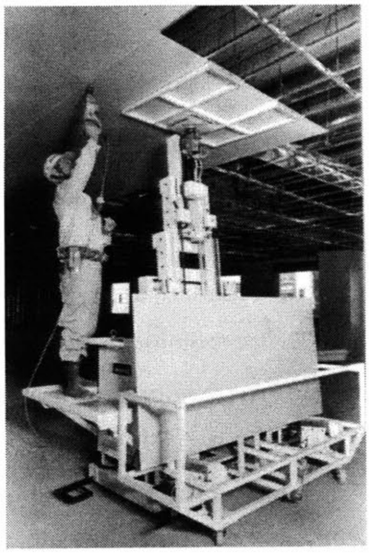

Figure 47 - Ceiling-Panel Positioning Robot (CFR-1) - *Shimizu Corporation, Japan*

Ceiling-Panel Positioning Robot (CFR-1)

The CFR-1 is a robot with a panel carrier which is easily separated when being transported. It has a base frame for traveling at panel length increments, an X-Y horizontal table use for positioning the panels, a panel holder which grasps the panels that is attached to the lifting arm, and a control box. It weighs 300 kg (660 lbs) and has four degrees of freedom, carries 20 panels at a time, capable of installing 25 panels per hour, and travels at a speed of 3 meters per minute (10 ft/min). The CFR-1 raises a ceiling panel and positions it into place. The operation is simple and positioning accuracy can be easily achieved. It eliminates scaffolding and releases workers from repetitive and error prone tasks that are very common with the traditional method.

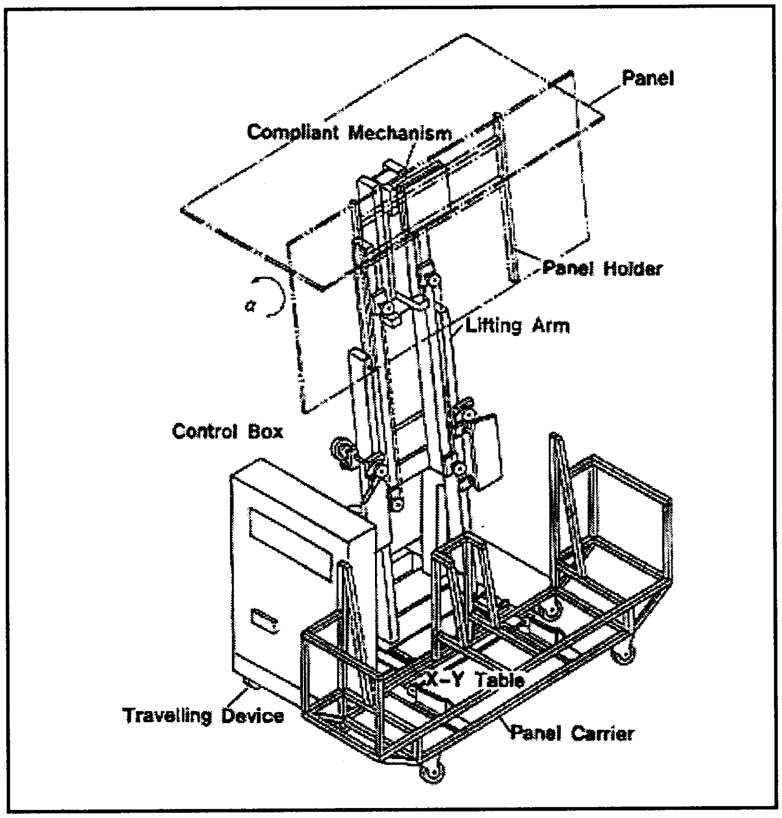

Figure 48 - Ceiling-Panel Positioning Robot (CFR-1) - *Shimizu Corporation, Japan*

Multi-purpose Traveling Vehicle for Concrete Slabs (MTV-1)

Finishing work for concrete slabs can be very tiresome and especially unsafe. The MTV-1 was designed to eliminate those issues with the main purpose of automatically grinding and cleaning concrete surfaces. It has two main modules, a power steering mechanism, a computer, a series of sensors, and batteries all located within the vehicle module. The cleaning module consists of a brush motor, a couple of filters, a dust container and a rotating brush.

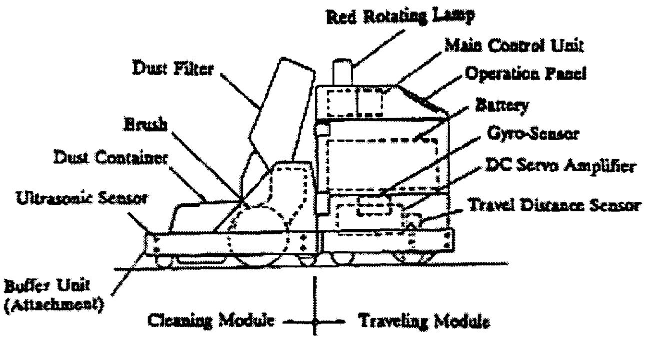

FIG. 5. Components of MTV-1 for Cleaning Work (Courtesy of Shimizu Corporation)

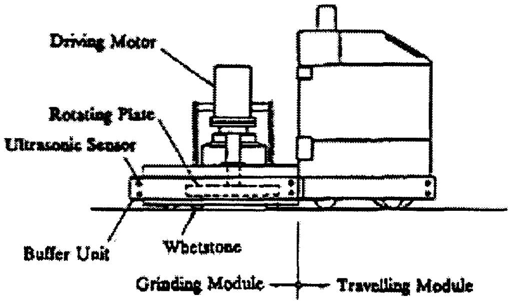

Figure 49 - Components of MTV-1 for Cleaning and Grinding Work - *Shimizu Corporation, Japan*

The two main features of the MTV-1 are that the work and the vehicle modules are separate; therefore, the modules for each task are interchangeable and it has the sensor ability to automatically travel along its path and avoid obstructions of the working site. The traveling direction of the robot is controlled by gyrosensors while the traveling distance is measured by the encoder attached to the measuring wheels. Other sensors include an ultrasonic device that gives the robot the ability to avoid collisions and traveling algorithm that studies the shape of the space as it travels around the area. It has the cleaning capability at 8 sq. m/min. (80 sq. ft/min.) and grinding at 2 sq. m/min. (21.5 sq. ft/min).

Concrete-Floor Finishing Robot (FLATKN)

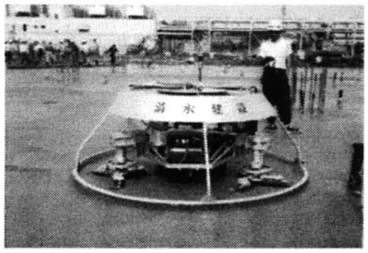

Figure 50 - Concrete-Floor Finishing Robot (FLATKN) - *Shimizu Corporation, Japan*

The three steps to the concrete-floor finishing robot are leveling, wood-floating, and trowel-finishing. Traditionally, the trowel-finishing step requires a very skillful worker posturing at an uncomfortable position for a long period of time; therefore, FLATKN was developed to alleviate workers from doing that task. It contains travel rollers, a power trowel, a controller, and a guard frame.

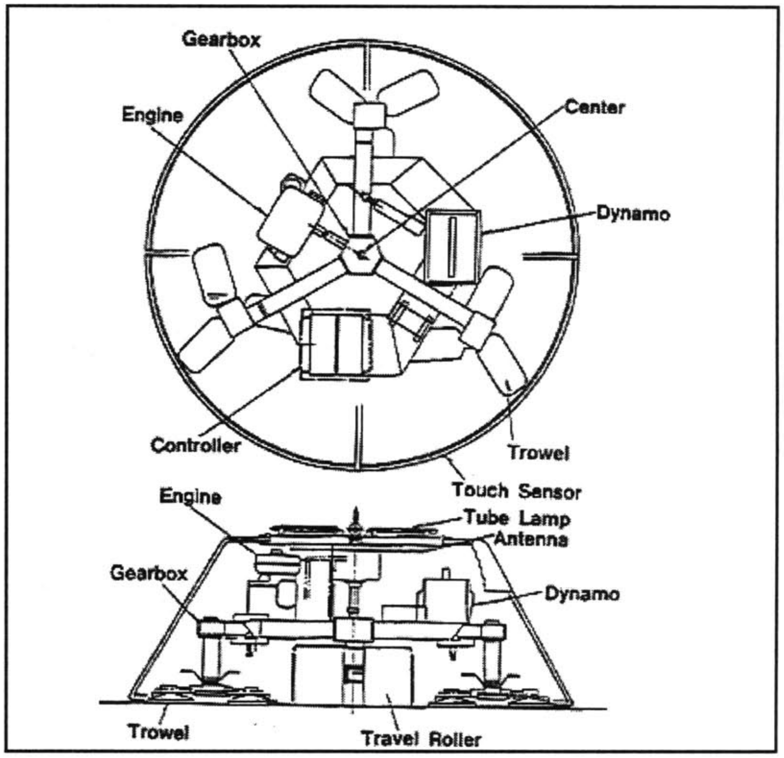

Figure 51 - Concrete-Floor Finishing Robot (FLATKN) - *Shimizu Corporation, Japan*

The robot's movements are controlled by DC motors powering the rollers that are attached to the main frame. As for the power-trowel mechanism, it has three arms which have three trowels at each end. It is powered by a gasoline engine and rotates along its axis as it spins around the traveling device. It also contains a small generator thus allowing it to be more mobile by eliminating electric power cables, and it has touching sensors that can detect obstructions in its work path. In addition, it also can be controlled remotely in order to determine a uniform finished surface which can be difficult to measure automatically. Several important attributes of this robot include its fine finishing accuracy, tight contact between the concrete and the trowel, and the trowel load can be adjusted according to how much the concrete has hardened.

Wall-finishing Robot (OSR-1)

Finishing tasks such as spray painting high-rise buildings can be very dangerous when done by the conventional method; therefore, the OSR-1 (Ohi Saikaihatsu Robot) was developed as an automatic spray-painting system for high-rise residential buildings to eliminate those risks.

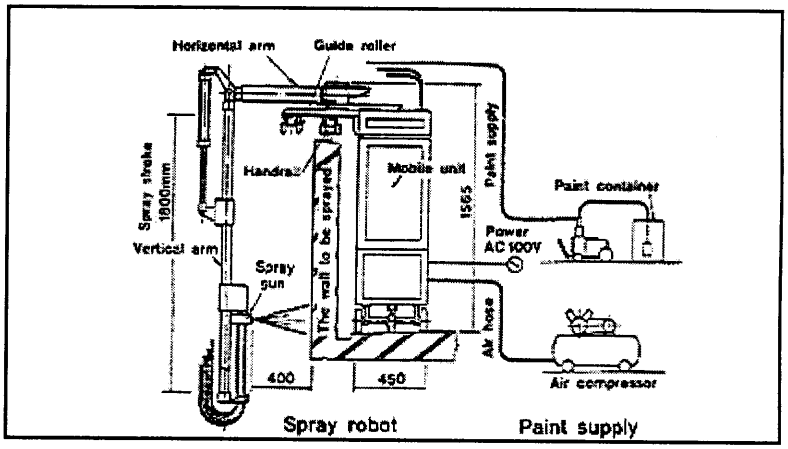

Figure 52 - Wall-Finishing Robot (OSR-1) - *Shimizu Corporation, Japan*

The OSR-1 consists of a guiding, traveling, and controlling device as well as a horizontal and a vertical arm that has a spray gun traveling up and down on it. The actual spray work is done on this vertical action in intervals by the traveling device. The guiding device controls the traveling paths with the assistant of a handrail, while the horizontal arm rotates automatically at uneven surfaces. It weighs 223 kg (491 lbs) and can travel at a speed of 20 m/min (65.5 ft/min). The main advantages of this robot are to reduce the number of workers traditionally required for this operation, increase safety, and get rid of the necessity for scaffolding.

Spray-Coating Robot (SB Multi-Coater)

This SB Multi-Coater automatically sprays different coating materials onto exterior walls of multistory buildings. The three main purposes of this robot are sealer coating, material spraying, and top coating. It provides a very smooth and even surface superior to a skilled worker. In order to provide for a uniform spray, a reciprocating spray is performed by a pair of guns mounted at an angle that can change directions when required.

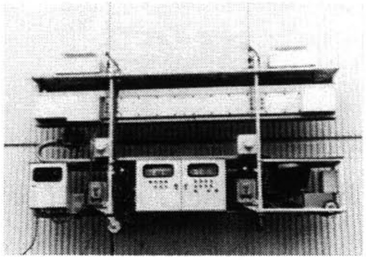

Figure 53 - Components of Spray-Coating Robot (SB Multi-Coater) - *Shimizu Corporation, Japan*

Hung by wire ropes from a trolley that runs on a rail attached on the rooftop and located at the top of the wall, the SB Multi-Coater can be started wirelessly. The procedures start as follow:

1. The material is loaded.
2. The automatic coating program is set.
    - **a.** Materials are selected.
    - **b.** A traversing pattern is selected.
    - **c.** A coating width is determined.
3. Operation through the controller:
    - **a.** The coater is lifted to the top.
    - **b.** The coater starts automatic coating.

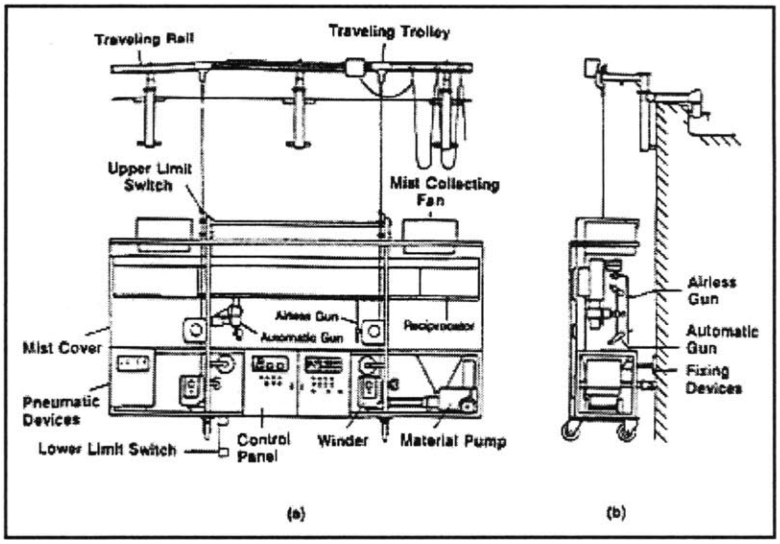

Figure 54 - Components of Spray-Coating Robot (SB Multi-Coater) - *Shimizu Corporation, Japan*

This process is five times faster than the conventional method and it only requires having one worker controlling it from the ground.

Automatic Silo-Lining System (SALIS)

To eliminate "cracks" in structural walls and upper slab of reinforced concrete silo, this system automatically sprays a single-liquid type hydrophilic urethane resin on the lining once it has been injected with epoxy-resin. Some key features of the systems are the elimination of any peeling or breaking of the concrete caused by impact, prevention of powdery explosions, and removes the possibility of poisonous effects.

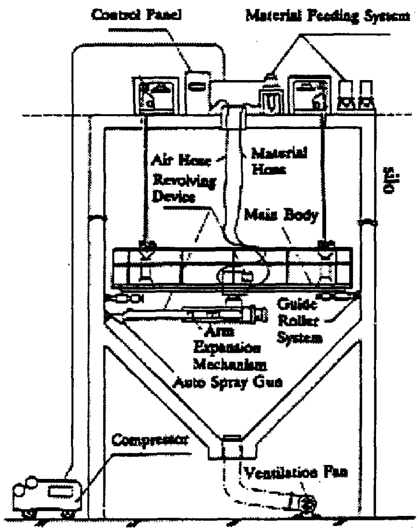

Figure 56 - Components of MTV-1 for Grinding Work - *Shimizu Corporation, Japan*

Activated Concrete-Cutting Robot

This cutting device was developed for concrete sawing and core-stitch drilling. Used for decommissioning of nuclear facilities by removing radioactive debris, the robot uses a diamond blade saw and a diamond hollow drill. The controlling component of the robot is separated from its main body in order for the operator to direct its movements from a distance.

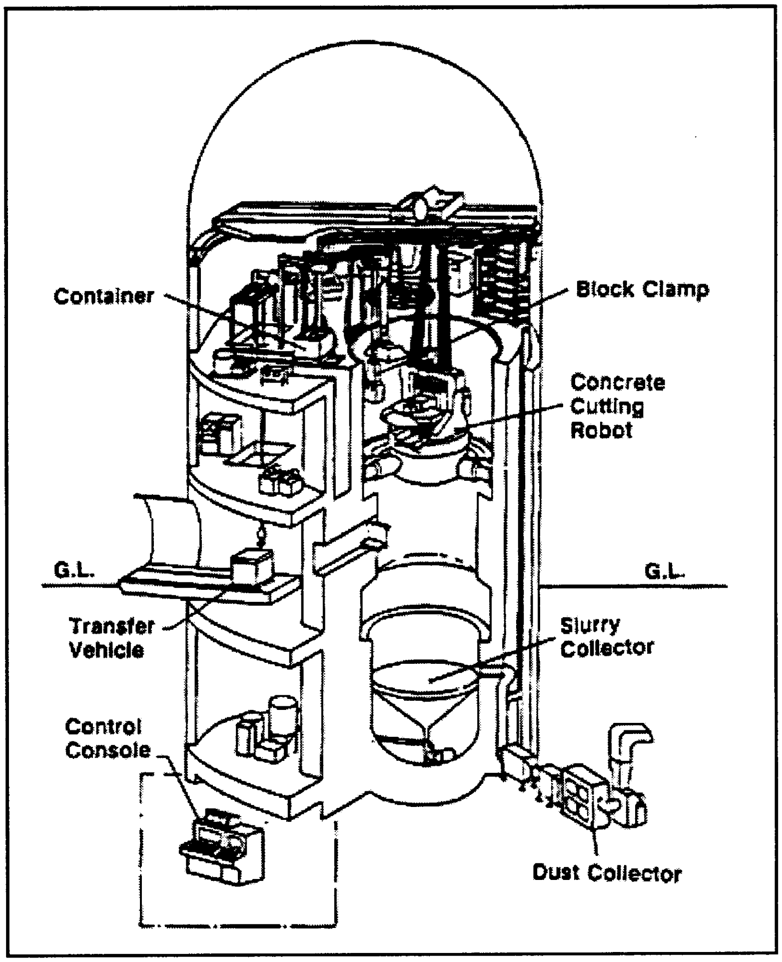

Figure 57 - Concrete Cutting Robot - *Shimizu Corporation, Japan*

An original prototype of this robot was developed in 1982 for testing purposes and the design of an actual applicable robot began in 1984. It weighs 16.5 tons, has five degrees of freedom, cylindrical formed coordinate system, 300 kg (661 lb) load capacity, and uses sequence control method. It was put to use in the dismantlement of the Japan Power Demonstration Reactor (JPDR) power plant in 1989.

2.4.5 OVERALL RESULTS

In general, the robots and systems described in this chapter have demonstrated that they are all capable of increasing productivity, enhancing the quality of work, improving accuracy as well as efficiency, and undeniably, advancing the level of safety within the construction environment. However, the one key element that was left out of the discussion and is often ignored in these types of papers, but yet has always played the vital role in delaying the progress of construction automation is the production cost of these systems and robots. But without a doubt, these systems are costly to produce even to the largest affluent corporations. Hence, funding and investments that are necessary for this type of research and production are mostly provided by the top, well-financed construction corporations as well as federal government funded programs.

Nevertheless, these robots and systems will continue to improve and the cost to produce them will become the norm as the level of automate technology advances and soon enough, these systems and robots will be a natural and fundamental part of our daily construction process.

Note: This section summarizes a research paper that was written by Roozbeh Kangari and Tetsuji Yoshida on various prototypes of construction robots in the June, 1989 issue of Journal of Construction Engineering and Management, Volume 115, No. 2. For more information on this and many other journals of this type of development, please refer to the wide collections of the Journal of Construction Engineering and Management.

CHAPTER 3:
PROPOSING A NEW SYSTEM

3.1 Rapid-prototype engineering

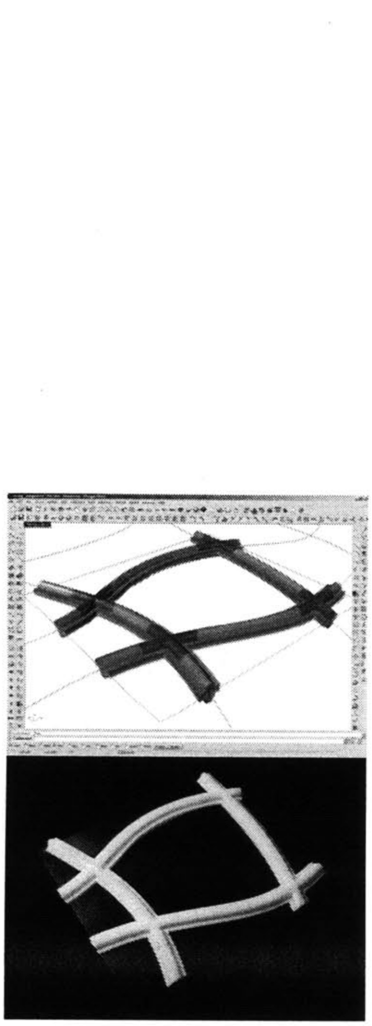

Figure 58 - Rapid prototype of a frame done with Fused Deposition Machine (FDM)

Rapid prototype machines today are costly, have several degrees of limitations, and notably, they are large and require plenty of controlled working space to operate. However, the technology is unprecedented. Whether it is solid free-form fabrication technique of milling or layered manufacturing method of 3D printing, this technology is becoming a new process for realizing the immeasurable possibility for design and construction.

When compared to virtual representation techniques, rapid prototype technologies offer designers, producers, and clients alike the ability to communicate, unequivocally, the design concept of a part or product with actual physical 3D representation in a form of prototypes. Additionally, with the aid of physical models, the cost of ongoing engineering changes can

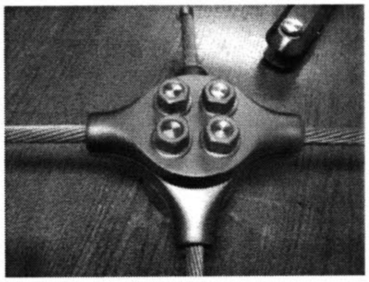

Figure 59 - Prototype joint by *Tri-Pyramid Structures, Inc.*

be diminished considerably and product development cycles can be dramatically reduced. Therefore, the conceptual idea of what rapid prototype technologies can offer is undeniably effective.

Although the technological categories of the rapid prototyping techniques are changing drastically, from several variations of 3D printing procedures to the numerous forms of subtractive methodologies, the fundamental principles and motives for using these techniques are essentially identical.

Stemming from the concept of rapid prototyping technology and discussion from a Media Lab course taught at MIT called "How to make something that makes almost anything", the Macro-Pick and Place System (MPPS) was designed to mimic the process of rapid-prototype engineering with unlimited potential.

Figure 60 - Z-Corp 3D printer - *Z-Corporation*

3.2 Macro-Pick and Place System (MPPS)

The one thing that all current rapid prototyping machines have in common is that they are always bigger than the objects that they create. Take the 3D ZCORP printer for example; measured 36 inches wide by 30 inches deep by 48 inches high, it can only produce parts that are at a maximum of 10 inches wide by 8 inches deep by 10 inches high. Unquestionably, since the industrial revolution and the traditional concept of machine fabrication, the majority of manufactured parts are produced within a working envelope.

Of course, this approach is undeniably logical and successful. However, what if the process was reversed? What if the product being produced is bigger than the machine that it creates? Then, can that particular technology be translated into real scale construction techniques?

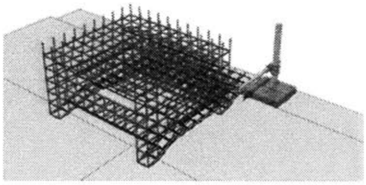

Figure 61 - Tessellation of a structure that is larger than the machine

Although to some degree, that technology exists today, such as specific-task construction robots doing repetitive duties. However, the idea of automated rapid modular fabrication linking various parts and joints all together to form a complex three-dimensional object at a construction scale has never been realized. With this new technology, it would not only create an entirely new typology for design and construction methodology, but also it would increase the levels of productivity and performance for the design and construction processes. Thus, this idea is simple and rational, but nevertheless difficult to achieve.

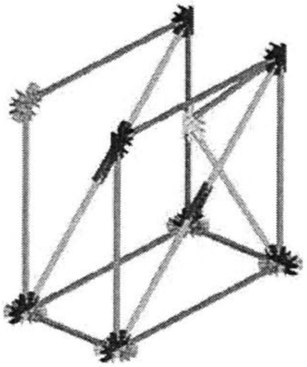

Figure 62 - K'NEX toy construction system - *K'NEX*

The MPPS was motivated by the ideology of rapid prototype technology with the desire to rapidly and efficiently construct a macro-scale structure assembling various pre-manufactured joints and members. In many ways, MPPS is a type of machine that can be seen as a multi-purpose do-it-all robot. It has the ability to tessellate a structure with its mobility and can be easily adapted to use various attachments in order to perform other necessary tasks. However, the initial purpose of this particular prototype technology was to recognize at a conceptual level the physical characteristic of any 3-dimensional object at real scale.

Theoretically, MPPS seeks to enhance the conventional methodologies of design and construction with the traditional technology of snap connection and modular components, imitating the idea of building with Lego, K'NEX or any similar toy connector building systems.

3.2.1 The Process

More detailed descriptions of the four unique stages of this process will be covered more in-depth in the next section

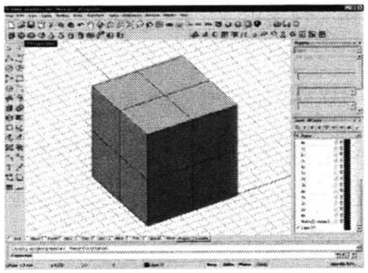

Figure 63 - A simple 3D box created in Rhinoceros

(3.3.1 STAGE ONE); however to briefly summarize the process, first it starts with a three-dimensional CAD model designed with any of the 3D parametric application such as Rhinoceros or CATIA.

The next step involves the exporting procedure. Similar to any of the 3D printing processes, the output stage starts with converting the 3D type file to a stereolithography (STL) type file. This data is then gathered and sent remotely to the on-board computer of the MPPS.

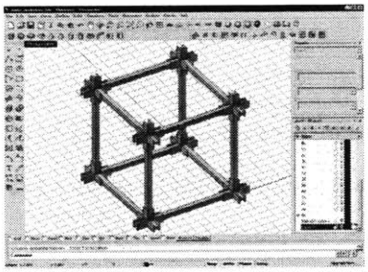

Figure 64 - The 3D box is then converted to recognizable parts

Once received by the MPPS, the built-in application then converts the given data into recognizable parts and members as well as strategically calculates the precise locations of each component.

Once each part is located on a three-dimensional grid, the MPPS then uses a local GPS coordinator to establish the exact location of any given part on any given site.

3.2.2 The Model

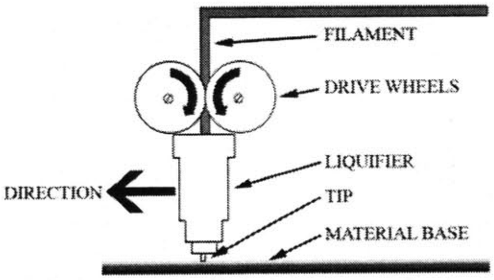

Figure 66 - Fused Deposition Machine extrusion process

The initial purpose of the MPPS model was to replicate objects at the scale of the current rapid prototyping technology. That is limited to a relatively desktop size and volume. Similar to any of the three-dimensional printing processes, such as the Fused Deposition Modeling (FDM) technique that operates by sequentially depositing discreet slices of plastic or wax material, or the 3D ink-jet printing technique introduced by ZCORP that models layer by layer from powder that is bound by a proprietary liquid. The MPPS looks to imitate these processes but instead of supporting materials or proprietary substances, it would generate the three-dimensional forms by snapping together a variety of physical parts that are made up of members and joints.

During the testing stages, several iterations and prototypes were developed for the purpose of understanding the physical nature of the machine. Using rapid fabrication techniques and machines available, the various functions and the physical parts of every prototype were developed from scratch. Designed in 3D, part by part, these models were developed to identify critical mechanical issues of the prototypes such as overall weight, balance, friction, etc.

At the same time, understanding that at a "desktop" scale, the machine's physical behavior is entirely different than those at a real scale construction application. These limitations include the inability to determine the actual work load; therefore the actual working mechanics cannot be determined. In addition, since the working envelope was quite smaller, the actual working space could not be established. Furthermore, the objects and parts being simulated were achieved using scaled tools and components, and as a result, the ability to realize the actual real-life production performance was undetermined.

3.2.3 The Parts

The very critical complimentary components that were needed to complete the MPPS assembly system were the parts that were required to construct the physical object. Similar to any snap connection structure such as Lego blocks or K'nex, there are male and female members that would interconnect when pressure is applied to one source or the other.

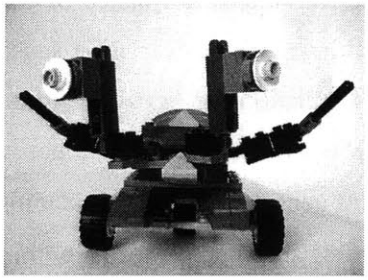

Figure 67 - Lego toy construction system - *Lego, Inc.*

These MPPS parts were made up of two types; one being the joint, the "male" member and the second being the strut, the

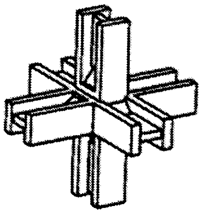

Figure 68 - Typical "male" joint member

Figure 69 - Typical "female" strut member

"female" member. These parts were intended to be custom fabricated simultaneously accordance to their specificity. The custom joint determined the angle and direction in which the strut will be placed. The strut was produced in the same manner; however, in this case the length of the specific strut was unique.

In order to understand and recognize the characteristics of how these parts work in conjunction with one another, over a dozen varieties of struts and joints with unique features were developed and tested. These parts were simulated both virtually as well as physically in order to examine the distinctiveness of how they connect. Some worked well in terms of connectivity, while others worked poorly due to the lack of contact surface and the brittle nature of the materials used when producing them.

A final design for the parts has not been determined; however, it was recognized that parts which gave more flexibility at their contact point when being snapped together performed vastly better than parts that had rigid connections during contact.

3.3 The Stages

Within the process, there are several sequential stages that the MPPS requires to complete in order to accomplish the necessary tasks. First is the utilization and performance of 3D parametric software. Parametric realization is crucial in a sense that it is necessary to understand the relationship between virtual and physical properties of objects. In addition, parametric comprehension is becoming the next generation of software tools used for the design and understanding of complex forms within the design and engineering industry. Therefore, there is a need to apply this practice to the MPPS technology.

The required second stage involves the output procedure that communicates between software and hardware. The third stage is the conversion of the data from abstract geometries to identifiable components, such as distinguishing where the joints and the struts should be located. Lastly, the fourth stage is the coordination between the location of the components within the 3D model and the actual site.

3.3.1 STAGE ONE

Parametric Software

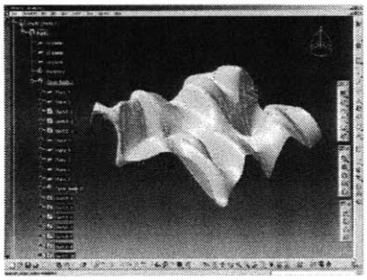

Figure 70- Parametric surface designed in CATIA

For years, mechanical engineers and industrial designers alike have been working with software tools that have enabled them to design with the computers in ways that are not available to architects. With these design software applications, they offer the designer the ability to adjust the different variables and parameters that can alter and define the shape of any simplify or even complex geometry, objects or assembly. As a result, engineers and designers now have the capability to manipulate and study alternative solutions efficiently, rapidly and parametrically. This innovative method is called parametric design.

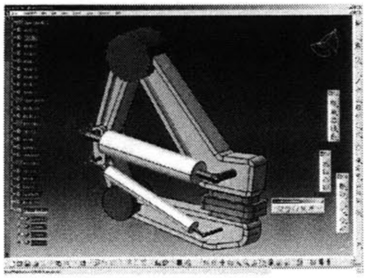

Figure 71 - Mechanical detail designed in CATIA

Until recently, architects have come to the realization that modeling software intended for other design professions can be their solution to the on going struggle to build and design with complex geometries. In addition, they are taking the next step in working directly with the software's underlying geometric functionality to customize some of the parameters for specifying various types of projects.

However, there are obvious limitations that negate the full functionality of the software application, such as accommodating to the various project configurations, workflow, and direct communication awareness between design intent and construction. Additionally, even with the necessary adjustments and alterations to the software inherent code, it's in their nature that majority of these programs as well as the computers used to run them are still not capable of handling extensive-detailed 3D representations of large building scale assemblies.

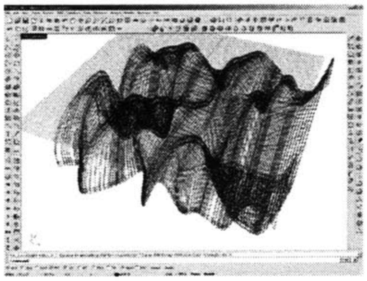

Figure 72 - Parametric surface designed in Rhinoceros

With the emergence of CATIA (Computer Aided Three-dimensional Interactive Application), a software developed by Dassault Systemes' as a PLM (Product Lifecycle Management), solutions for digital product definition, collaboration, manufacturing processes and digital product simulation of all sizes can be realized[8]. The world of parametric design now has the potential to realize unimaginable possibilities.

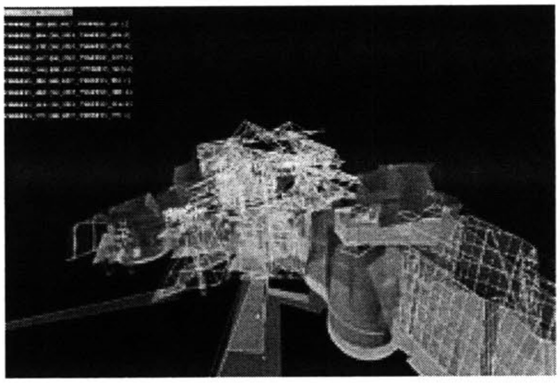

Figure 73 - CATIA master model by Gehry Technologies - *Gehry Partners, LLC.*

Used extensively by Gehry Partners and Gehry Technologies to develop the many exotic surfaces and geometries of Gehry's buildings, CATIA's programmatic nature seems to be an ideal match for controlling the MPPS applications. Since the MPPS would require that the application takes on the ability to understand and the capability to manipulate complex objects and geometries at different building scales. However, the one negative aspect of using a program such as CATIA is that it's very expensive in terms of its price tag and the general service support. Therefore, the need for the implementation of a customized program that not only exclude

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[8] CATIA is Dassault Systemes' PLM solution for digital product definition and simulation. More information on this product please visit Dassault Systemes' website at http://www.3ds.com/products-solutions/brands/CATIA/

the many redundant options within the application, but also designed exclusively to run the many specific stages of the MPPS should be considered.

Implementation

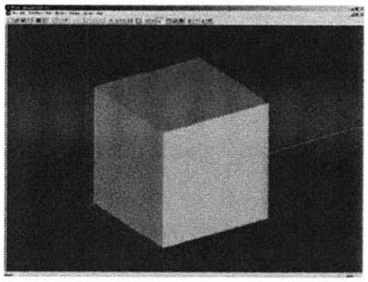

Figure 74 - An object designed with any 3D parametric software

In order to comprehend the intricate forms of the intended object, the capable parametric software within the MPPS application needs to be flexible enough to allow for a real time manipulation of various shapes and geometries. But it is also critical that once the form has been established and developed, the possibility of modification to that particular form should be minimized and only adjustments to not fully formed components should be allowed. Since dependencies within the linking components of the object is so critical, altering a linking object, especially once it has already been established, can ruin and complicate the rest of the undeveloped components.

3.3.2 STAGE TWO

Output

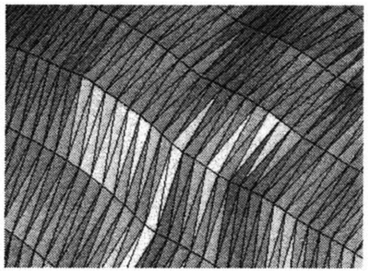

Figure 75 - Detail of an STL triangulated type surface

Within the rapid prototyping industry, the .STL file format has become the primary standard data transmission format that is necessary to interact with any stereolithography machines. This format works by approximating the surfaces of any solid model with a variety of triangles replicating the intended sizes and shapes of any objects. Besides the utilization of outputting 3D physical objects, the STL format is not applicable for any other purposes. Incapable of sending or understanding actual engineering data, this file format was basically designed to provide simplified meshes formed from specified data that can only be understood by stereolithography machines.

This type of format seems to be suited perfectly for the exporting function of translating unique data structures from the design application to the MPPS operational software. Since it simplifies the complex nature of any object's shape and size, very little transmission data is required to communicate with the targeted machine. Therefore, the receiving machine does not need to contain large memory storage capacity or a powerful and expensive on-board processor to be able to handle the large non-STL file type.

Thus, once an object is completed, the design software distinguished and generated the boundaries within the form from the computer model, a 3D mesh models is created in using one of the surface rendering functions and an STL (Stereolithography) file is produced and transferred to the on-board computer of the MPPS.

3.3.3 STAGE THREE

Conversions

This stage is very detrimental to the success of the MPPS and a focal point in its ideology and purpose. Currently, there is no known application software out there on the market that can take the information from an STL file and convert the given data into the kind of identifiable structure that the MPPS would need to recognize.

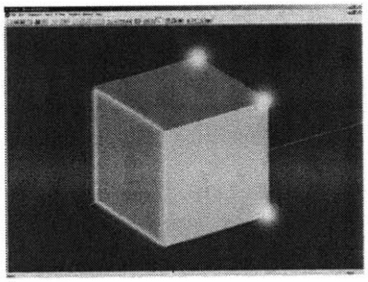

Figure 76 - Unique edges and points of the object are being recognized by the software

However, logically this conversion stage can only work if the given simplified geometric data can be translated into components that are familiar to the MPPS. The edges along the object would need to be broken into segments that are associated with the dimensions of the struts and joints. Then the placements of these components need to be located within the geometric volume of the object.

3.3.4 STAGE FOUR

Locator

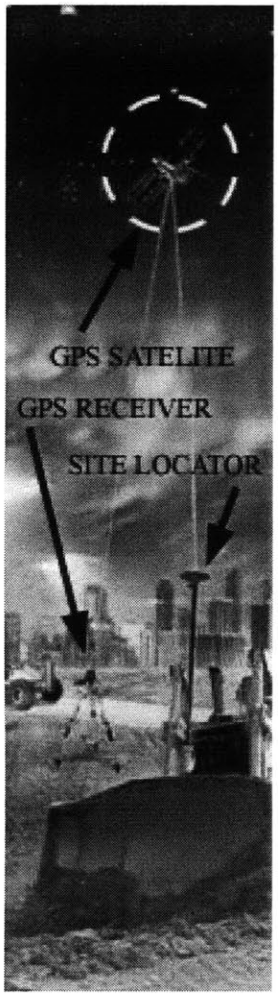

Figure 77 - GPS recognition system - *Topcon Positioning Systems, Inc.*

Navigation and positioning of each component is crucial to the successful execution of the MPPS. However, this process of course-plotting and path-finding globally has always been quite cumbersome. Over the years different kinds of technologies have tried to simplify this operation and all have had some degree of drawback.

As a result, the U.S. Department of Defense developed, originally intended only for governmental use, an exceptionally precise form of worldwide positioning system. This resulted in the creation of the Global Positioning System (GPS) that is now widely employed by both the military and civilian applications.

Today, the conceptual system of the GPS has become integral part of any normal daily activities and the beauty of the system is that it can be operated independently by tailoring to the needs of every user. In addition to the satellites being accurate, they allow unlimited number of users to calculate their precise location at any given moment by using a one-way signal path from the satellite to the receiver.

With localized GPS products that are commercially available today, such as Topcon's 3D-GPS+ system and Arc Second's Indoor GPS technology, the MPPS looks to these devices to strategically position the newly acquired components within a three-dimensional grid of the computer model and associate it with the actual construction site. A more descriptive look at how these localized GPS technology works will be covered later in Chapter 4 (4.4 Working Area) and Chapter 6 (6.1.3 Metrology and Localized GPS).

In addition, there have been several advancements in the area of metrology. The Robotics Research Group at the University of Texas at Austin (UTRRG) has developed the next generation of 3D measuring devices. Their main focus is in the area of metrology research for robotics which involves the advancement of methods to measure a robot's positioning with extreme accuracies. Along with considerations of several layers of complexity, variations of measurement speed, accuracy, cost, and required operator skills were as important in the development of these measurement systems.

CHAPTER 4:
MACHINE'S CONSIDERATIONS

4.1 Design Constraints and Considerations

Since the conception of the MPPS idea, over a dozen of various machines types were designed for investigation. However, during the later phases of design and development, only nine versions were considered for analysis, while three out of the nine were physically produced as prototypes. The rest were analyzed through the use of computer simulation for visual understanding of varying behavior of the mechanical components.

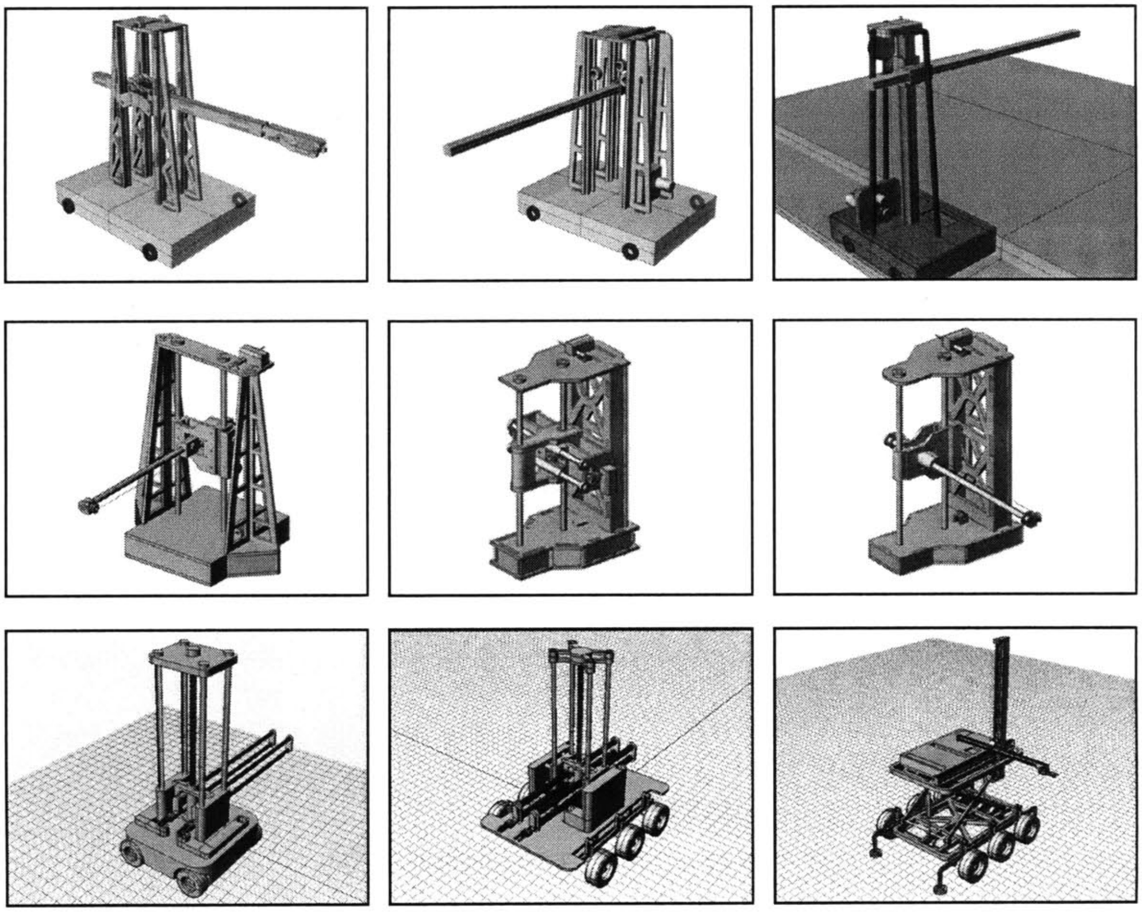

Figure 78 - Top Row (L-R) - Version 1, Version 2, Version 3. Middle Row (L-R) - Version 4, Version 5, Version 6. Bottom Row (L-R) - Version 7, Version 8, Version 9.

Figure 79 - Laser cut model of an earlier concept machine

During the early stages of development, the first few versions of the machines were conceptually thought of as solely being produced through the use of rapid prototyping technique such as the laser cutter and the FDM (Fused Deposition Machine). Although at a desk-top scale, this proposal was deemed a reasonable option. However, precision, tolerances and moving components proved to be difficult to achieve due to the natural properties of the limited materials available. Therefore, other means of productions needed to be considered such as custom manufacturing and purchasing stock machine parts.

The design criteria of the machines were simple; determined the number of degrees of freedom (DOF) required for the machine to accomplish its tasks, account for the various load sizes of the parts and the components and their locations, and recognize and consider the various types of working areas.

4.2 Degrees of Freedom (DOF)

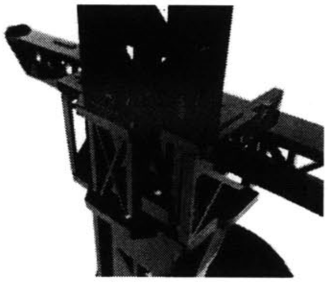

Figure 80 - Detail of a laser cut model of an earlier concept machine

As a rule of thumb in mechanical design, in order to determine all the parts of a particular manipulator and its movements, the number of independent position variables needs to be specified which results in the number of degrees of freedom that the manipulator is required to possess. In other words, DOF refers to the number of different ways in which a mechanism can move or rotate.

In typical industrial robots, the number of joints usually equals to the number of DOF largely due to the fact that the manipulator is usually an open kinematic chain and that each joint position is usually defined with a single variable. In the case of the MPPS, it was determined that six degrees of freedom were required in order for it to successfully perform its duties. These six DOF's are divided into two main areas of positioning and orientation. Three degrees are used to position a particular component in space while the other three are required to orient the same component to the exact location.

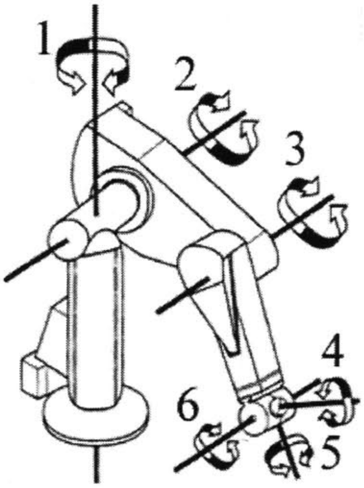

Figure 81 - Six Degrees of Freedom (DOF) of a typical robotic arm - *Department of Energy (DOE) OSH Technical Reference*

For this particular application, it is necessary for the positioning DOF to be generous, meaning it needs to have the ability to transfer any components within a large working envelope. On the other hand, the orientation DOF is much smaller since it only needs to compensate for the minor movements that are required after the general placement once it has been positioned.

Even though all of the machines that were designed during the development phases met the necessary requirements, however, there were quite a few disadvantages. Whether they are friction between materials or tolerances between the parts or even the variation with the types of motors, each machine had to be modified profusely from one version to the next.

4.3 Load Size

High efficiency is the main ingredient in the determination of effective design of any machine. In other words, a machine should be able to have a large enough work load to keep itself busy over an extend period of time while reducing the number of major changes that may require resetting. However, this rationality for the relative sizes of these machines is often based on essential stock machine tools and ready-made components. In turns, this limitation regulates the entire strategy for the consideration of load sizes, efficiency factor as well as the overall operating and manufacturing cost for development.

Another common rule of thumb for the design of any manipulator is the approach to determining the relationship between payload and machine size. This rule simply states that for every Kg of payload, approximately 10 Kg of machinery is required; basically, a one to ten ratio. Therefore, if the payload is a part that weighs 5 lbs, the manipulator will have to weigh approximately 50 lbs. In addition, that total would then need to be added on along with other required supporting components and equipments and the machine's weight can increase exponentially.

Since mobility is one of the necessary criteria for the MPPS, the weigh factor plays a critical role in the design of the base for the machine in that it has to be very responsive in terms of movement and agility. The initial intention was that the machine's base would be fixed on a track system that can accurately control a particular axis.

However, fixed-guided and track technology limits the responsiveness of the system in terms of error adjustment that can be common for this type of system. Additionally, the time needed to install and remove the tracks would decrease the efficiency factor; therefore, it was determined that by having wheels controlling the base, higher efficiency and similar accuracy could still be achieved.

For the design intention of the latest version of the machine, it was aimed to replicate Blockbot which is an automated block wall construction robot developed by the department of civil engineering at MIT in 1988. Since the majority of the design structures were already determined and the functions of the machine were very similar, only minor necessary design alterations were done for it to become the next version of the MPPS.

4.4 Working Area

The condition of the required working site was initially thought of as a fixed predetermined working surface that has all the essential guidelines for establishing a specific reference system. Again, this requirement was eliminated due to the overwhelming limitation that it has on the flexibility factor of the system. Currently, the concept of the working site is described as any terrain in a controllable environment that can accommodate for freely autonomous movement.

However, since the working site needs to be recognized by the computer environment in order to generate the required local coordinates, some site preparation might be mandatory before any machine operation can take place. This groundwork could be a variation of the determination and placement of markers for the perimeter of the working area, removal of obstructive particles and debris, leveling out the crucial paths of travel, and the installation of required reference indicators.

Additionally, with the advent in 3D scanning technology, large scale metrology and positioning devices such as Arc Second's INDOOR GPS system can provide solutions for real time monitoring. Furthermore, it can observe motion tracking and large scale precisions of the entire working environment by utilizing GPS sensors that can be placed anywhere on the construction site. These sensors have the ability to track and record data that are used in controlling and navigation of various maintenance cranes, robots, and other moving machinery and tools. With the addition of this type of system, an entire new solution for understanding and controlling every aspect of the working area will soon be realized.

4.5 Coordinate Systems

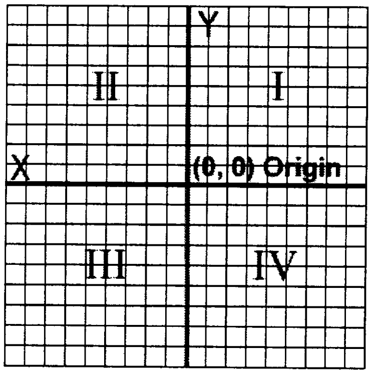

Figure 82 - Two-Dimensional Cartesian coordinate grid

In geometry, physics or engineering, the mathematic term for a coordinate system is explained as a system that assigns sequences of objects, in some cases, real numbers to each point in an n-dimensional space. However, depending on the context, these real numbers can mean complex numbers or variation of elements of some other type. It is imperative to determine the appropriate form of coordinate system in order to apply the mathematical design criteria to decide on the functionality of the machine.

There are many types of coordinate systems such as Cartesian, polar, and cylindrical coordinates. Although there are several variations, in engineering however, these are the three systems that are often recognized and are commonly used.

4.5.1 Cartesian Coordinates

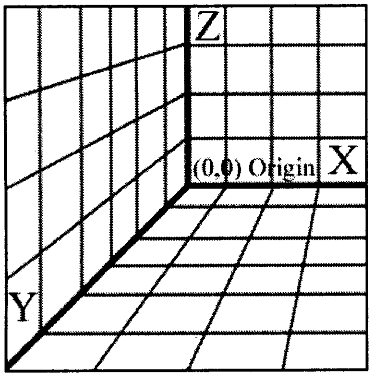

Figure 83 - Three-Dimensional Cartesian coordinate grid

Also known as "rectangular coordinates", Cartesian coordinates are widely used in computation and engineering. They provide a recognition system that can determine the angles, locations and distances for moving parts, components as well as the machine itself. The Cartesian coordinate system is divided up into four quadrants. Moving counterclockwise from the top right section are quadrants I, II, III, and IV. It can also be either two-dimensional or three-dimensional.

In the 2D model, the familiar X, Y coordinates meet at a right angle to form a planar grid that can mathematically determine the location of any given point on the same plane. The 3D system however, incorporates the Z coordinates perpendicular the 2D coordinates creating a three-dimensional field that can determine the location of any given point on a three-dimensional grid.

4.5.2 Polar Coordinates

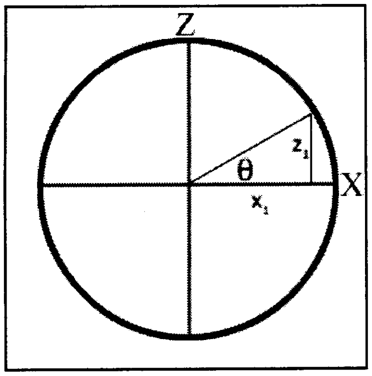

Figure 84 - Polar coordinate system

The term polar coordinates frequently refer to circular coordinates that are on a two-dimensional surface. This coordinate system can identify any given point on a three-dimensional grid by determining the distance from some fixed feature in space and one or more opposite or extended angles. For machine design, it is widely used to determine the capabilities of a robotic arm by calculating the arm's linear motion.

4.5.3 Cylindrical Coordinates

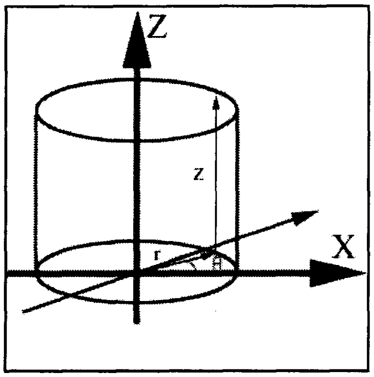

Figure 85 - Cylindrical coordinate system

The cylindrical coordinate system is a three-dimensional system similar to the 3D Cartesian system, which essentially extends circular polar coordinates by adding a third coordinate which measures the height of a point above the plane. Cylindrical coordinates are useful in analyzing surfaces that are symmetrical about an axis, with the Z-axis chosen as the axis of symmetry.

In terms of machine design, this system is useful in determining the main support angle of rotation and the requirements for the base bearing that is required to carry additional components. The need for analyzing the relationship between the horizontal and vertical movements can also be determined. Normally used in the design of a robotic arm, this coordinate system can assist in the calculation of mechanical allowance as well as interference.

4.6 Further Considerations

There are many other variables that are necessary in determining the effectiveness of machine design that are beyond the scope of this research. One such variable is the thermal effects that can contribute to the overall structural integrity of the machine. Thermal attributes such as deflections, stresses, resistance and expansions of not just a single component but a combination of mating materials could directly affect the consistency of the machine operations and the general life cycle of the entire system.

In addition, a very important aspect of machine design that should also be considered is the machine assembling procedure. Overlooking the notion of assembly can be very costly if changes are necessary in the later stages of the machine's process. Along with the simplicity in the assembly procedure, maintenance issues such as replacements and repairs to the various active and inactive parts and components should also be considered.

Note: This section only described in brief a very few relevant and fundamental laws of machine design considerations and criteria. For more information and elaborated descriptive details of several others design components, please refer to "Theory and Problems of Machine Design" a Schaum's Outline Series published by McGraw-Hill in 1961. This book was written by Dr. Allen Hall, Alfred Holowenko and Herman Laughlin. In addition, other design criteria elements can be found in "Fundamentals of Machines Elements" published by WCB/McGraw-Hill in 1999 written by Bernard J. Hamrock, Bo Jacobson and Steven R. Schmid.

CHAPTER 5:
BREAKING DOWN THE MECHANICS

The design implementation of the overall concept for the machine is comprised of several actuation procedures and physical components. The determinations of movements were based on the comprehension of simplified manipulator technology and the process of traditional robotic assembly methods.

Through the understanding and consideration of existing robotic and automated technologies, the articulation of the machine was broken up into two major categories. One being the action steps that the machine are required to take and the other being the arrangement of primary components that complete the system.

5.1 Components

As a result, it was established that there were 5 major components:

1. Hopper - container for the parts.
2. Base - controls the X-axis.
3. Tower - controls the Z-axis.
4. Arm - controls the Y-axis.
5. Gripper - controls the grabbing and releasing of the parts.

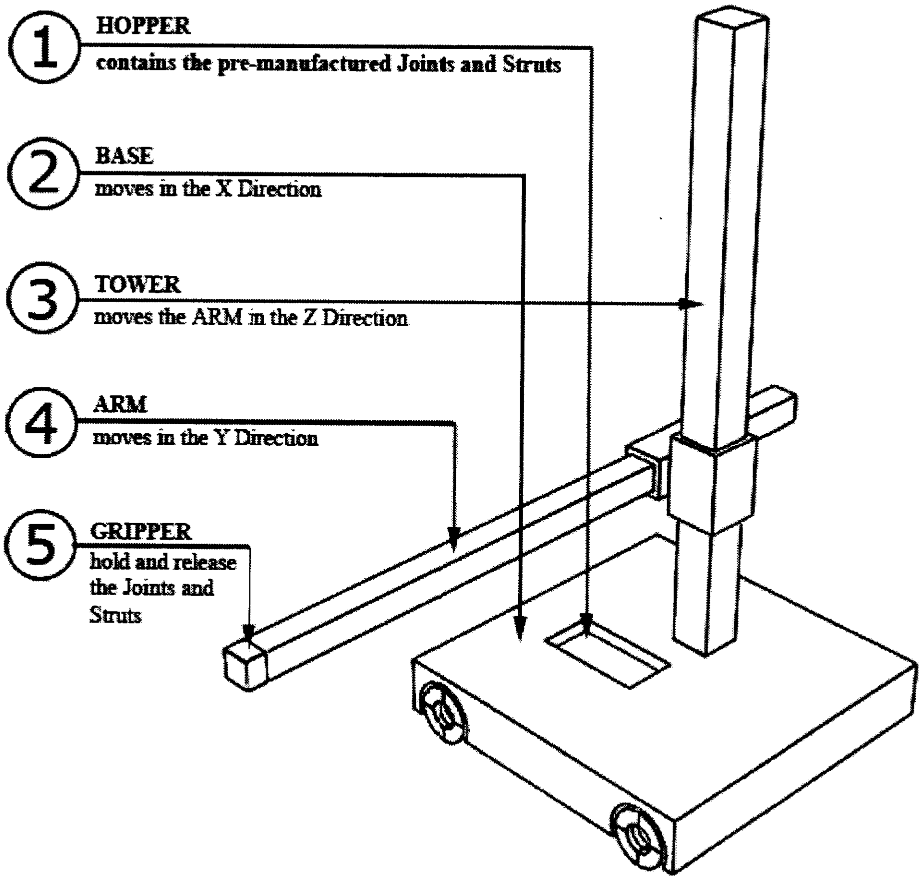

Figure 86 - Machine components diagram

5.2 Actions

And there were 5 action steps that are required of the machine:

1. The Arm locates the parts in the Hopper.
2. The Base moves to the correct location.
3. The Arm moves to the correct Z-position.
4. The Arm moves to the correct Y-position.
5. The Gripper controls the rotational movements as well as the gripping and releasing of the parts.

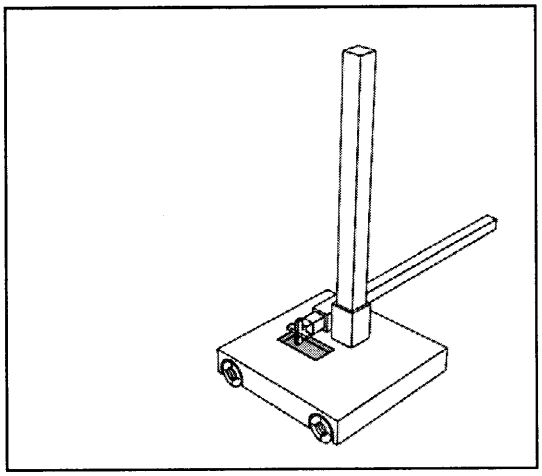

Figure 87 - HOPPER - Joints and Struts container - *ARM locates the joints and struts in the hopper*

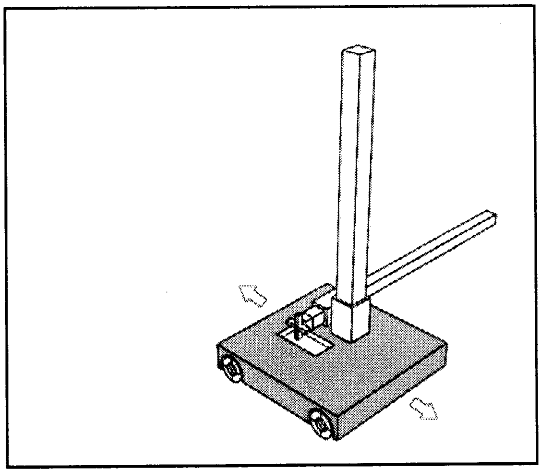

Figure 88 - BASE - *Controls the machine in the X Direction*

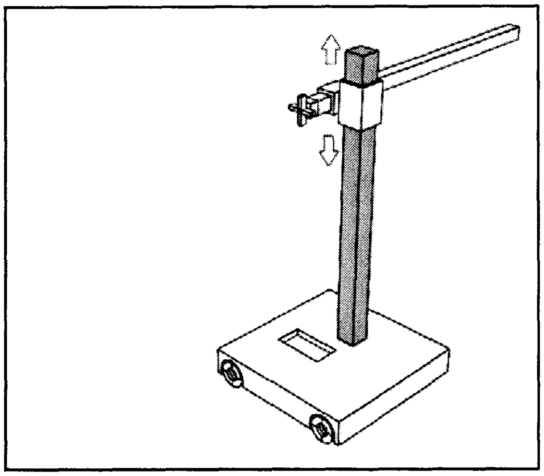

Figure 89 - TOWER - *Controls the ARM movement in the Z Direction*

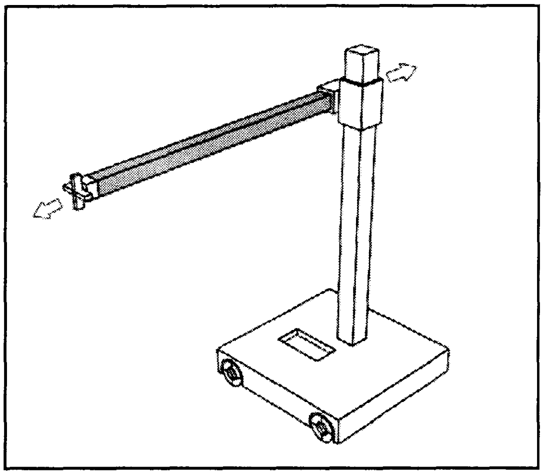

Figure 90 - ARM - *Controls the ARM movement in the Y Direction*

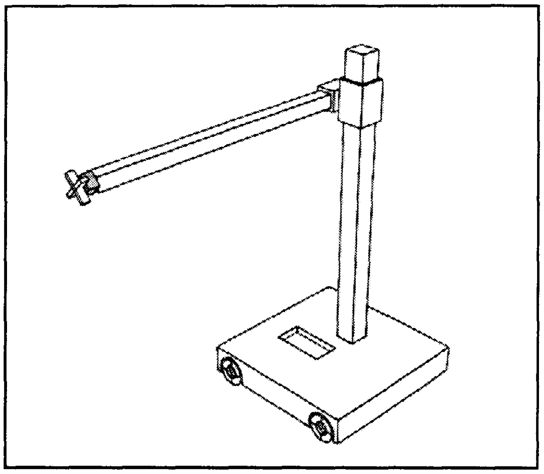

Figure 91 - GRIPPER - *Controls the* ***rotational*** *movement,* ***gripping*** *and* ***release*** *of the joints and struts*

5.3 The Manipulator

Figure 92 - An early version of the pick-and-place machine with 3-Link connection

Traditionally, a manipulator is thought to have three main elements. A base support, an arm, and an end effector or gripper. In the case of the MPPS, there are five components; the tower, an arm, a gripper, and a base that includes a hopper. Although all of the components are critical to the mechanism of the machine, the one unit that carries out the majority of the important tasks by the machine is the arm. It not only carries the part that is often called the work-piece and locates it in the precise location in space, but it also needs to be intelligent enough to communicate with the on-board computer to adjust for the unpredictable inaccuracy from freely autonomous movement.

Within the arm or the tower support are the drives or motors that actuate the arm. For feedback purposes, sensors are mounted on the arm for two different functions: 1) to sense the actions and status of the arm itself. 2) To sense the surrounding environments in relation to the arm and the entire machine.

5.3.1 Links and Joints

Also important within the arm is the link that is sandwiched between the support and the gripper. It is a rigid member that supports the loads carried by the arm. Typically it is hollow to reduce the weight of the arm in addition to providing enough space for gearing and other electrical controlling components.

Contained in the linking module, there are the joints that can rotate, slide or a combination of both. Conventionally, six commonly used names are given to describe the joints:

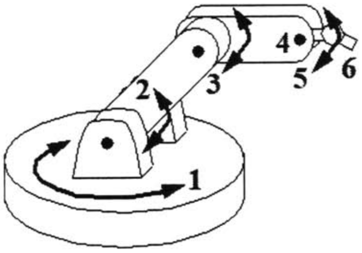

Figure 93 - Typical manipulator configurations of links and joints

1. Waist rotation
2. Shoulder pitch
3. Elbow pitch
4. Wrist pitch
5. Wrist yaw
6. Wrist roll

5.3.2 Gripper

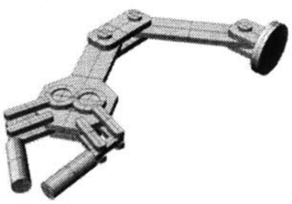

Figure 94 - An early gripper design

Throughout the development stages, there were several considerations for the grasping and holding techniques. One such idea was the use of vacuum pumps where instead of grasping; a hose at the end of the arm makes continuous contact with the part through the use of air pressure. However, it was determined that the parts to be carried varied so much in shapes, sizes and weight that this technique would be less favorable.

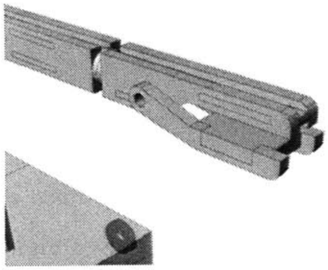

Figure 95 - An early gripper design

Another suggestion was to use electromagnets. An electromagnet works like any other magnet by creating a magnetic field that attract things made of steel or iron. However, a regular magnetic field works by connecting permanently from one side to another until it is separated by a greater force. With electromagnets, the magnetic field is temporary and can only exist when electric current is flowing through it. Since there was a need for parts that can be produced rapidly and efficiently, the idea of having them made out of steel or iron immediately eliminated this option.

Other proposals were hooks, various types of adhesives, scoops, along with grippers with three or more fingers. In the end, the decision overwhelmingly leaned towards the two-finger gripper. This technique was not only easy to operate, but also simple in design as well as to control and manipulate. The understanding that went into the design factor of the gripper includes the ability to hold the parts without damage, to be positioned firmly or rigidly while the object is being operated on and to accommodate parts of differing sizes. Additionally, this design also allows for the self-aligning jaws to ensure that the load stays centered and requires the jaw to make contact at a minimum of two points to ensure that the part doesn't rotate or shift while being positioned.

5.3.3 Driving mechanism

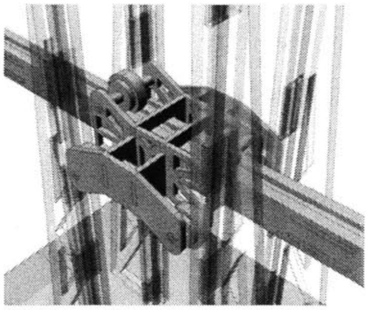

Figure 96 - An early design for a vertical driving mechanism driven with motors and tracks

The mechanisms required to provide movements and the changing of speed to the components of the machine can be apparatuses such as gears, ball screws, harmonic drives, different kinds of linkages, and variations of motors. These motors can be electric, hydraulic, or pneumatic. Additionally, motors with harmonic drive gears make it possible for controlling the changes in speed with high accuracy and can be compact. Backlash, defined as the difference between the tooth space and tooth width within the gears of actuators, has been a major factor in the accuracy of numerous drive mechanisms. But with harmonic drive gears, backlash can be reduced to very small amount and possibly to a point where there is a return of "zero backlash".

5.4 The Motors

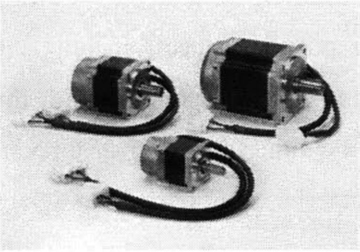

Figure 97 - Servo motors

In the world of mechanical design, motion is often generated by various conversions of mechanical energy. This energy can either be generated gravitational forces or any other form of energy. In the present day, the most commonly used form of energy is electrical energy. Therefore, it is crucial to understand the relationship between the mechanical and electrical energy that involves the analysis of electric motors that use electro-magnetic principles to provide mechanical movements derived from the interaction of two independent magnetic fields.

5.4.1 Electric DC motors

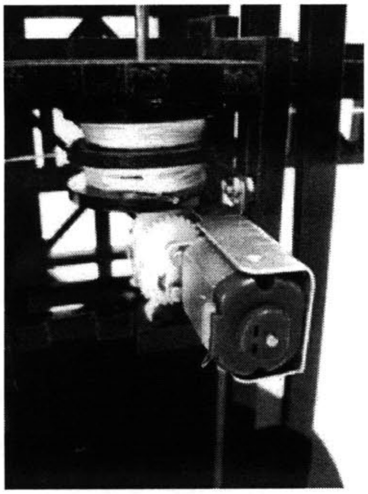

Figure 98 - An electric DC motor attached to an early machine concept

There have been many arguments over the efficiency of DC motors and stepping motors. The use of DC motors for high-accuracy positioning can have many advantages as well as disadvantages over stepping motors. The one main advantage is the increase of linear torque-to-power ratio along with a larger torque-to-volume ratio. Other advantages include the possibility for a more precise positioning, more rapid response time, and higher degree of holding torque at specified positions.

On the other hand, the requirement of closed-loop operation in order to achieve accurate positioning, the need for reverse current switching in order to change motor direction, the wearing of brushes over an extended period of time, and the higher cost of simplified positional setting are some of the disadvantages that make the use of DC motors to achieve high precision less attractive.

5.4.2 Stepping motors

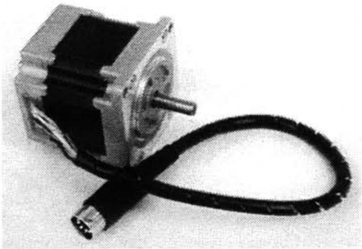

Figure 99 - Stepper motor

With the ability to be fully synchronous in a way that it can continuously move at a speed with no long-term speed position error, stepper motors are often better at achieving high accuracy than DC motors. Other positive aspects include the ability to provide a more stable and precise operation with the open-loop control, the capacity to be either uni-polar or bipolar, the convenience of providing a superior positioning for lighter loads, and lastly, the reduction in motor cost for more simplified positioning tasks.

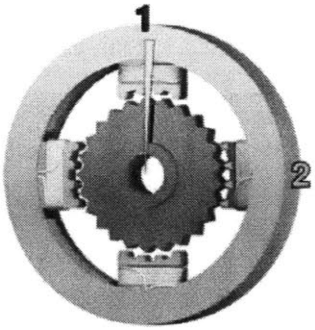

Figure 100 - Interior of a stepper motor. The top electromagnet (1) is turned off, and the right electromagnet (2) is charged, pulling the nearest four teeth to the right - *Wikipedia, Created by Wapcaplet*

Inside the steeper motor is a set of stationary electromagnets that are controlled by internal rotors that are made of permanent magnets that can be switched on and off electronically. Stepper motors have a fixed number of magnetic poles that can determine the number of rotations with each revolution. Therefore, it has the ability to determine precisely the travel distance determined by each rotation.

As with any motors, there are also disadvantages to stepper motors. When compared to DC motors, the stepper motors are larger in volume for a given torque requirement. In addition, the stiffness and holding strengths of the motor solely depends on the positioning of the motor gear. Furthermore, special circuits and ramping techniques are required for maximum efficiency as well as unsuitable for heavy loads that require high torques and have high disturbance factors.

5.5 CONTROL SYSTEM DESIGN

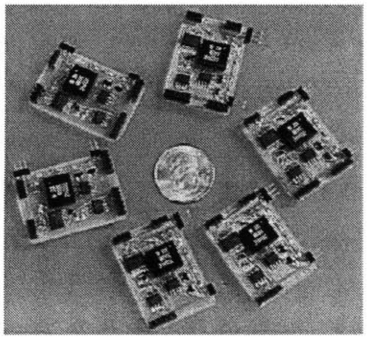

Figure 101 - MITes (MIT environmental sensors) - *Changing Places, MIT Media Laboratory*

The control equipments are essential in handling and directing the many sequences of the components. A very basic control may possibly be no more than a timing circuit that opens and closes air valves. Simple mechanical stops may also be used to limit movement that is necessary with any pick-and-place type machine. More complex controls may be steppers switches, computer logic devices, or a complete microprocessor controlling the various motors that drive the component links.

Additionally, sensory devices are needed to control and measure locations, distances, forces, torques, proximities, temperatures, and many other factors will be required as the

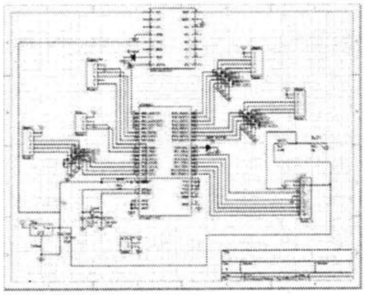

Figure 102 - Circuit board layout of control components for the prototype Version Number 6

more complicated the machine becomes. A very similar type of wireless sensor technology is currently being developed at MIT's Media Laboratory in the Changing Places Consortium. These wireless sensor components called MITes (MIT environmental sensors) are designed to be low-cost devices that can detect movements in objects and people within any environments. As a result of the advancement in these types of technology, the level of efficiency will increase and fluctuate depending on the accuracy of the sensors especially within a pick-and-place type of system.

Once the appropriate sensory type is established, the closed-loop of a motion control system can be easily determined. Complex control systems are certainly necessary as the degrees of freedom increase with any type of machine. Therefore, the motion controller has to be able to accommodate for the multiple closed-loop actions. Although a machine's controller might be required to control numerous closed-loops, the basic structure of any closed-loop control system remains. Indeed, the kinetic-dynamic chain is the main controlling components of the machine's control system.

As the complexity of the machine grows, it is necessary to address the relevant control system design issues such as specifying the desired output of a closed-loop control system, obtaining the exact dynamic control model, applying available quality sensory feedback information, and determining various control laws that guarantee satisfactory control performance with unique types of responses.

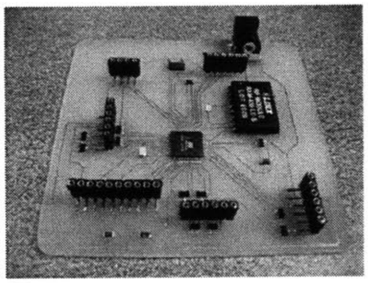

Figure 103 - Actual circuit board using the Atmel ATMega32 micro-controller to control Version Number 6

In the case of the MPPS, unquestionably sophisticated hardware and software are required to control the many components of its system. In the case for this particular system, there are several relevant types of control that are applicable.

They range from point-to-point, continuous-path, controlled-path, and servo feedback control.

5.5.1 Point-to-point

Simply put, this system has the ability to move from one specified point to another but cannot stop at arbitrary points that have not be previously designated. These are the simplest and least expensive type of system. They are driven by servos that are often controlled by potentiometers set to control manipulators at a specified point.

5.5.2 Continuous-path

This system works by determining the shortest distance between two points and can only stop at a specified number of points along a path. However, if no stop is specified, the autonomous movement may not stay within a constant curved path between those specified points; therefore, in order to achieve desired accuracy, an excessive amount of points may be required.

5.5.3 Controlled-path (Computed trajectory)

The control equipment on controlled-path machines can generate straight lines, circles, interpolated curves, and other paths with high accuracy. These paths can be specified parametrically, geometrically and algebraically with exceptional accuracy at any point along the path.

5.5.4 Servo and Non-Servo

Servo-controlled machines have the capacity for sensing their position and giving feed back to the sensed position with the idea of calculating the movement along a particular path that is needed to be followed. Non-servo machines do not have the means to determine whether or not they have reached a specified location. All controlled-path machines have servo capability to correct their path constantly when carrying out specified actions.

Overall, any of these types of control applications would work with the MPPS. Nonetheless, since MPPS is modeled after rapid prototype technology that uses a computed trajectory to control the majority of the machines, controlled-path application seems to be the most obvious choice. Its flexibility and accuracy in following computer generated paths makes it an ideal candidate.

5.6 TYPES OF APPLICATIONS

5.6.1 Sequence-Controlled Machines

The MPPS initial control operation consists of picking up parts at a known fixed location and feeding them one by one to the hopper specified on the machine. This type of control system is called sequence-controlled. In addition, there are many other variations for controlling a pick-and-place type of applications, such as on-board cam action, electrical sequencing relays, or hard-wired circuits which are connections that are permanently soldered or crimped together so that they cannot be altered by electrical control.

However, in order to understand and invent new application techniques, it is crucial to analyze the various existing application techniques involving different types of industrial machines and robots, as well as investigating and clarifying the many typologies of robots and machines from welding applications to movable technology.

5.6.2 Playback Machines


Figure 104 - Mold injection machine

Less intelligent production equipment such as stamping presses, forge presses, die-casting machines, injection molding machines, and many types of metal-cutting machines are known as playback machines. They are usually loaded and unloaded by similar machines or robots that can be programmed to go through fixed series of operations and record in its memory. The human operator then commands the action sequences to repeat the operations indefinitely. Generally, the training operations are done at a slow speed, although the actual production operations are typically done at full speed. These machines are productive; however, over time their efficiency factor will decrease as parts and components will wear out depending on the rate of operation.

5.6.3 Spot Welding

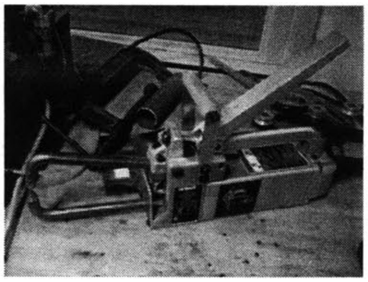
Figure 105 - Spot welder gun

In the manufacturing industry such as the automotive industry, a widely used process of joining two metal work-pieces together while maintaining high positional accuracy through the use of concentrated heat is known as spot welding. Instantaneously, the molten materials cool, and the two metals are permanently bonded. This process is typically used when joining steel sheet metals that are less than 3 mm (0.125 inches). Thicker stock however is difficult to heat up from a single spot, as the heat can easily flow into the surrounding surface creating incomplete fusion of the two joints.

Since there is usually resistance within the metal as it starts to liquefy, this delay allows for the process to be monitored in real-time to ensure a perfect weld. It also provides for the spot welders an opportunity to be completely automated; hence many of the industrial robots found on assembly lines today are spot welders.

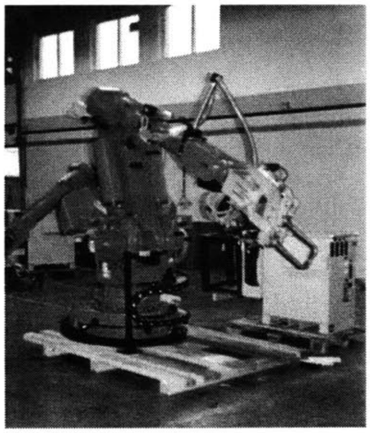

Figure 106 - Spot welding robot - *robot-welding.com*

As mentioned, for thicker materials, spot welding might not be appropriate. However, for applications such as joining of studs, the stud welding operation is commonly used. Stud welding is a different form of spot welding where a bolt or specially formed nut with a flange around it, is welded on sheet metal. These bolts are generally automatically fed into the spot welder. Nevertheless, this application requires more procedural sequencing that can lead to a more complex and highly cost control system.

5.6.4 Adaptive Machines

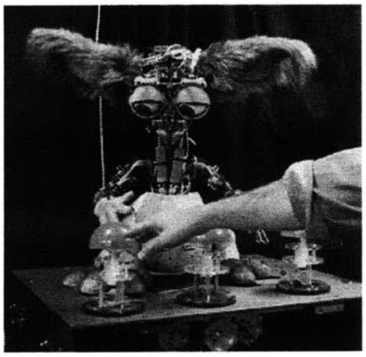

Figure 107 - Leonardo - an interactive robot that can learn and adapt to social environments - *Robotic Life Group, MIT Media Lab*

Adaptable robots and machines have the capability to sense their environment and modify their actions to respond accordingly. However, customized built-in programs within the computer control system are necessary to make these actions possible. According to recent research studies, the two main areas of robotic technologies that support in the development of adaptive computer-controlled robots for industrial use involve programmable industrial robots with performance and costs acceptable to industry, and artificial intelligence research in pattern recognition, visual sensing, tactile sensing, and robot control systems.

5.6.5 Assembly of Small Products

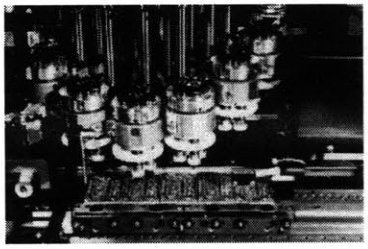

Figure 108 - Electronic assembly chip shooter line - *Indak Manufacturing Corporation*

These adaptive machines are normally applicable within specific areas. One such area is the assembly of small products. Through the uses of guided sensor technology, this application technique employs the robot's vision to identify parts, either in feeders or coming down conveyor belts, and direct the robot to pick up the part as well as position it in place. An important capability that is required in a control system of this type is parallel processing where tactile and proximity sensors are in conjunction with vision systems and assembly systems.

5.6.6 Adaptive Welding

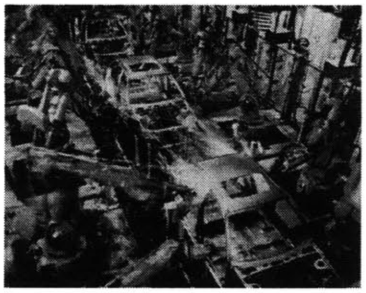

Figure 109 - Automotive assembly spot welding - *robot-welding.com*

As mentioned earlier, welding application is an accurate rapid joining process that has proven to be very beneficial in the manufacturing industry in terms of bonding strength. For automatic welding applications, both vision and tactile sensing are required to guide the welder to follow a seam. This is known as adaptive welding. Often, the parts to be welded are never cut precisely or aligned exactly. In these particular cases, a sensing laser beam is required on the machines to scan forward of the current welding spot in order to locate the weld seam.

Probes are other sensory devices that can also be used to sense the weld seam by touch. One simpler technique is called through-the-arc welding, where it uses of the arc of the weld itself to determine the shape of the weld seam.

5.7 Mobility

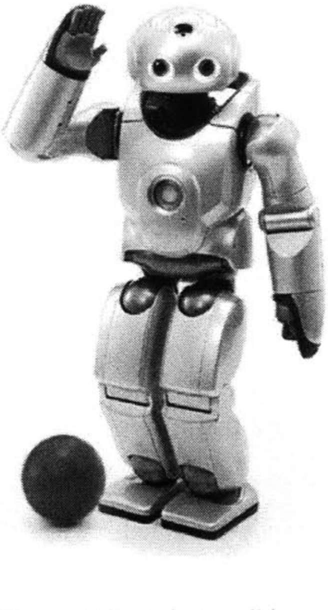

Figure 110 - Asimo walking robot - *Honda Motor Company*

In mechanical design, there have always been debates relating to the flexibility and usefulness between fixed and mobile robots. There are many advantages and disadvantages to both types. These discussions do not often go very far and vastly due to the slow progress of controlling technology, it usually relegates to the logical and straightforward option of utilizing fixed robots. Mostly, this is obviously due to the basic structure of machine design to minimize component's complexity while maintaining efficiency as well as accuracy. However, as technology improves, controlling methods will be more advanced and the level of effectiveness of mobile robots will surely improve.

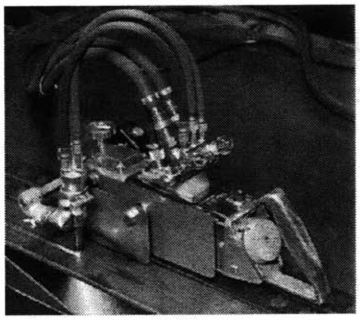

Figure 111 - Track guided plasma cutting device - *Koike Aronson, Inc.*

5.7.1 Fixed Robots

Currently, nearly all of production robots are mounted on a rigid base and bolted to the floor so that they could withstand the forces and torques applied when they are in motion. Evidently, there are several reasons for keeping robots fixed. One essential motive is simply economic; it is much cheaper to build fixed robots. Another important reason is again, the control issue; the more movements the robots are required to make, the more complex the controls have to be.

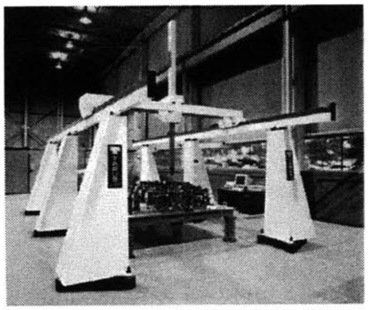

Figure 112 - Tarus CMM (Computer Measurement Machine) - *Tarus Inc.*

There are many variations of fixed robots. The most common type of this kind is the fixed robot mounted on a standard pedestal base. Another common type is the fixed robot supported from above. These ceiling mounted robots are often used where floor space is critical. Then there are fixed robots on tracks. The most common of these tracked types are welding and painting robots. However, majority of fixed and track robots pose several critical mobility problems such as readjustment for accurate positioning and handling of various slippages. The considerations in the placement of the power supply, air hoses, hydraulic hoses, electrical power wiring, and control wiring must be accounted for since they will be traveling with the robots.

Figure 113 - Roomba Intelligent FloorVac - *iRobot*

5.7.2 Mobile – Wheeled Robots

As in the case of track robots, the majority of them are mounted on wheels. However, currently there are no industrial robots in production that are independently mounted on wheels without any secondary support system. Although there are several hobby robots that are developed by this approach, they are very minimal in design and limited in their capabilities. They are more suited for uncomplicated tasks such as household assistants or similar toy items.

5.7.3 Mobile – Tracked Robots

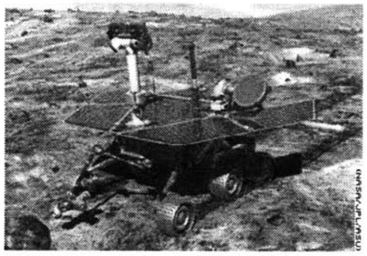

Figure 114 - NASA's Mars rover - *NASA, US*

Currently, there are a few mobile robotic arms that exist that are mounted on a track performing uncomplicated and effortless tasks such as transporters and carriers. These robots are very effective in terms of transporting particularly light loads. However, they are not autonomous but in reality a dependent teleoperator similar to NASA's rovers. These robots are essentially self-propelled anthropomorphic manipulator, which is entirely controlled by an operator.

5.7.4 Mobile – Legged Robots

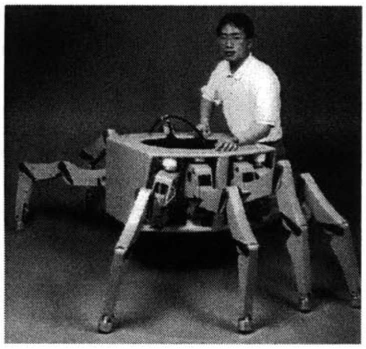

Figure 115 - Robug III: Intelligent walking and climbing robot. *Photo by Dr. Bing L. Luk, University of Portsmouth, England*

The intended purpose of legged mobile robots is for them to travel effectively through difficult terrain. Yet again, control components for a walking robot, especially an autonomous one, is difficult to achieve. On the other hand, there have been some demonstrations of such technology in the past. But they are still very basic and at times problematic.

5.8 Autonomous machines

There are several advantages that autonomous robots can bring to the manufacturing industry. One such advantage is reduction in production cost. Manufacturers understand and appreciate a simple fact when it comes to the actual cost of making any products. The realization is that their production cost can be dramatically reduced with the use of robots. Not only that the robots can produce higher percentages of quality parts and assemblies, but also reducing the overhead cost when compared to human workers. This is simply the result of eliminating the need for such benefits as worker's compensation and fringe benefits.

In the manufacturing industries, 30 to 50 percent of the overall base salary is dedicated towards these benefits. In addition, human workers are allowed by law for personal and fatigue allowance that can take up to 15 to 20 percent of the actual production time. Although maintenance and break down of the robots should factor into the equation, it is hardly comparable to human necessity.

Another advantage that autonomous robots can bring to the manufacturing industries is the increase in productivity. As a result, schedules, which are crucial in the performance of the industry, can be followed and maintained. Additionally, an improvement in the overall management control can be realized. Since all autonomous robots are computer-controlled, they are designated to carry out preprogrammed procedures with great accuracy and these activities can be recorded. This information then can be applied to improve scheduling, better control in planning strategy, and ease in the monitoring process of current and future operations.

Other important advantages in the utilization of autonomous robots are the increase in the product quality and their ability to be operable in almost any type of condition. Whether it is hostile or hazardous, robots are capable of working under these extreme circumstances. In terms of quality in production, an obvious factor that contributes to this is that robots are much better at achieving higher accuracy positioning than humans. Furthermore, the speed which robots can attain makes many complicated and nearly impossible tasks to human possible.

Note: This section only simplified and briefly explained the different types of machine design. For more information of this topic as well as many other types of machines, please refer to Allen Hall's "Theory and Problems of Machine Design" and Bernard J. Hamrock's "Fundamentals of Machines Elements."

CHAPTER 6:
MACHINE VERSION NUMBER 9

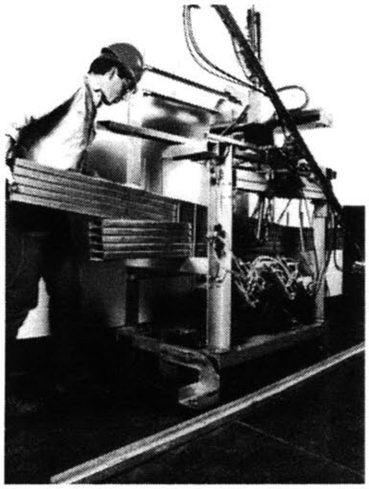

Figure 116 - StudBot is used for installing studs after a track is laid out - *MIT*

In 1987, researchers at MIT proposed a methodology to increase efficiency within the automated construction processes that tackles the issues of designating the construction processes into specific tasks. They designed and developed several prototypes of block laying and wall constructing robots. During the experiments, they tested and developed a variety of mechanical and electrical components that responded exceptionally. These tests include several iterations in the degrees of freedom, linear actuator-bearing assemblies and advanced angle and distance measuring sensors.

As mentioned in the machine design analysis chapter, considerations of existing technologies were highly regarded. Therefore, the latest version of the experimental machine called version number 9 incorporates several new components that were already developed by the MIT researchers. These developments include assemblies such as the hydraulic scissor lift and axis coordination arrangement.

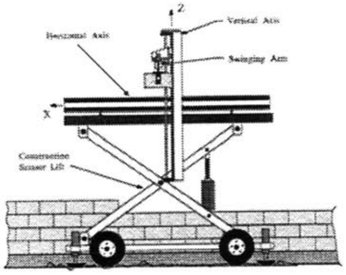

Figure 118 - Schematic view of WallBot - *MIT*

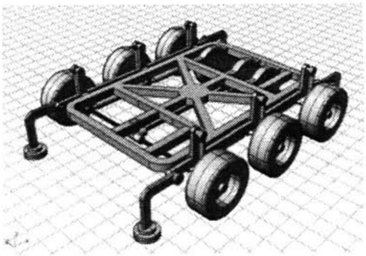

Figure 117 - Six-wheel base for Version Number 9

In addition, other newly added components were the six-wheel accuracy control base, which is similar to NASA's rover and the new placement for the containment of the prefabricated parts. Please bear in mind that majority of the detailed descriptions of the control systems and other mechanical components are beyond the scope of this research. Therefore, only considerations will be established while factual physical results cannot be determined until full functioning prototypes are developed and tested.

6.1 Major Subsystems

In version number 9, there are four major subsystems within the overall structure. They include:

1. The hydraulic scissor lift and the axial movements of the arm and gripper.
2. The containment of the struts and joints along with its delivery system.
3. The GPS system that determines key locations and the conversion software.
4. Determining the working environment of the site.

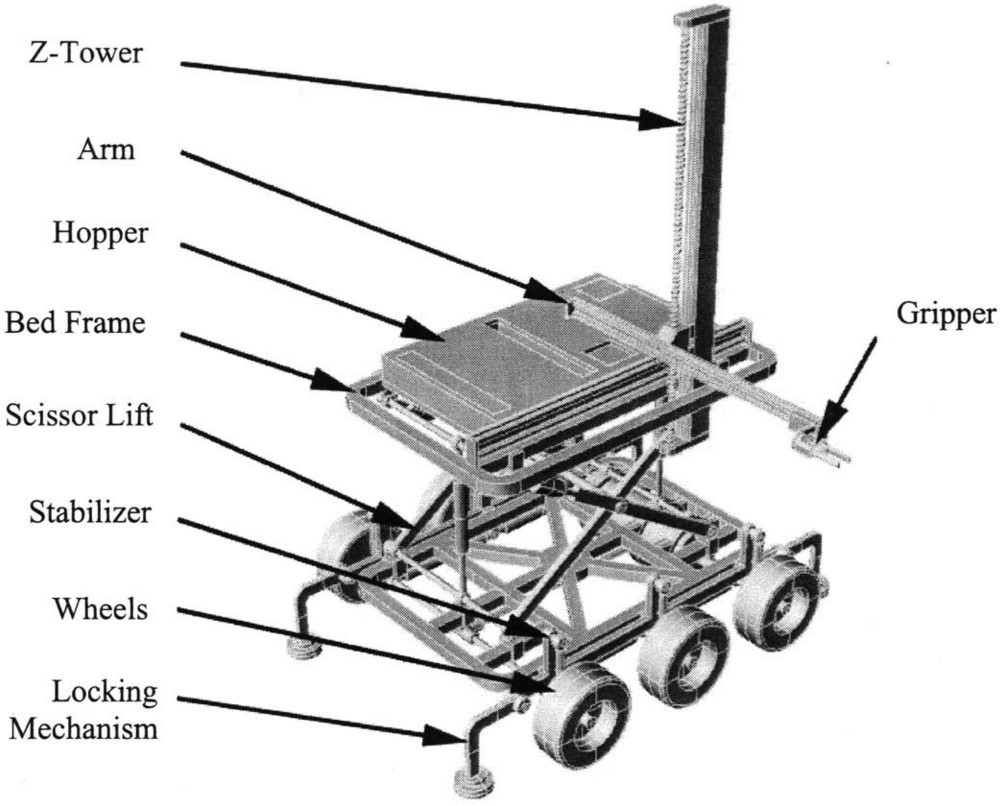

Figure 119 - Components of Version Number 9

These subsystems describe the general areas that are necessary for a successful execution of the process. As mentioned in Chapter 4, the design criteria of the machines were determined by the number of degrees of freedom, the location and variation of load sizes for the parts and the components as well as the recognition of the different types of working areas.

6.1.1 Axial Movement

Throughout the entire design development of this project, several positive and negative assessments were determined and established in terms of evaluating the designs. These rules set the groundwork for the design phase of these machines.

They include:

1. Linear axes are easier to control than rotary axes.
2. Machines that have rotary connections are more difficult to maintain and service than those of linear axes.
3. The shorter the cantilever length, the stiffer the structure.
4. The shorter the cantilever length, the higher the load capacity.
5. The more complicated the manipulator, the harder it is to control and wire.

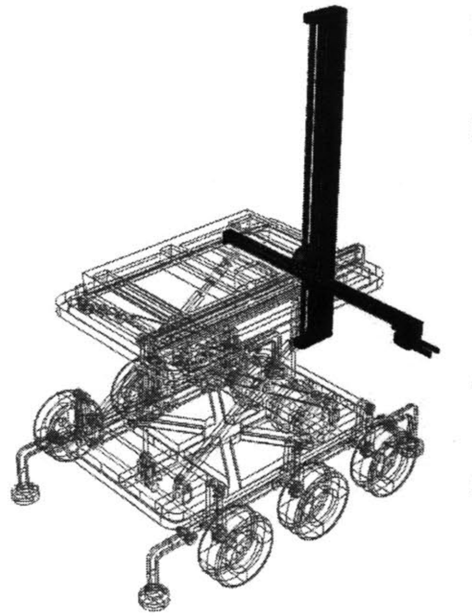

Figure 120 - Tower with arm necessary for horizontal and vertical axial

These established rules dictated the design of version number 9. The axes placements of this version remain similar to all of the previous versions. However, by placing the X and Y axes on linear servo-actuator bearing tracks instead of pneumatic power actuators resembling the other versions, it provides greater accuracy and better control to the moving components. As for the Z direction, the arm is controlled by a vertical ball bearing shaft that is often used in high speed movements that required low coefficient of friction.

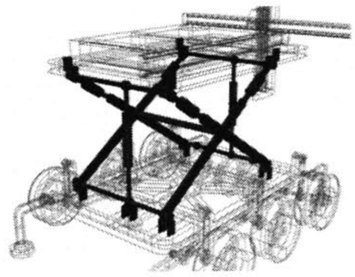

Figure 121 - Hydraulic scissor lift

A very unique addition to this version is the hydraulic scissor lift. This powerful lift not only is capable of handling exceptionally heavy loads but also maximizes the vertical reach while limiting the travel distance of the arm in the Z direction. The alleviation for a shorter tower makes for a more rigid structure.

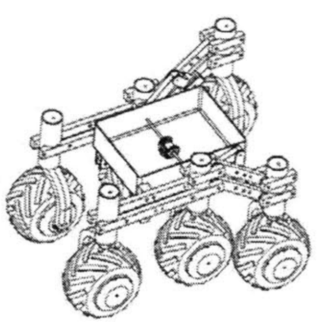

Figure 122 - A design of a rover with six intelligent wheels - *Eric Poulson, Utah State University*

The other distinctive supplement to this version is the transformation from a four-wheel base to a six-wheel base vehicle. The wheels are arranged in a rectangular pattern with equal spacing along the side. A well known fact in mechanical design is that the more wheels a vehicle has the smoother the drive[9]. However, with more wheels the suspension design has to be more complex, therefore adding more complication to the control system. Nevertheless, the more multifaceted the suspension design, the better resistance between the machine and the rough terrain will become.

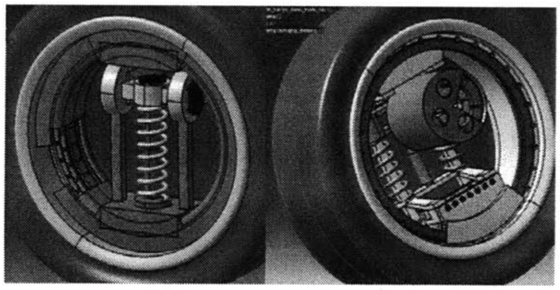

Figure 123 - Wheel with built-in independent suspension system designed by Patrik Kunzler - *Images and model by Patrik Kunzler, MIT*

The key design strategy for this version is the six matching wheels with each containing a built-in independent drive, steering, and control systems in order to operate the vehicle autonomously. The suspension system was designed to distribute the entire weight of the machine evenly between the wheels with dynamic springs and dampers to mediate terrain changes if necessary.

6.1.2 Containment of Parts

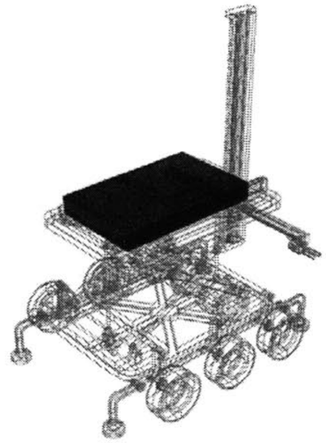

Figure 124 - Containment of parts

The carriage that contains the unique parts sits on top of the scissor lift. This detachable container which is known as a hopper is essentially a rectangular box divided into two sections with slots for distributing and receiving the parts. One section contains the struts and the other section contains the joints. Similar to a magazine of a gun, these hoppers are prepped in advance by stacking the parts one by one inside the spring loaded slot. They are then stacked on site at a particular location for the MPPS to locate and reload when necessary.

Initially, the rapid-prototype concept for the MPPS is for the hopper to have to capability to produce their own unique parts, therefore increasing the efficiency factor. However, in

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[9] More details on the design of a rover with six intelligent wheels written by Eric Poulson at Utah State University can be found at: http://www.autonomoussolutions.com/research/press/EricPoulsonThesis.html

order to regulate and minimize the overall weight and maximize the mobility aspect of the real scale construction machine, the decision was to separate the production portion from the delivery system.

6.1.3 Metrology and Localized GPS

Figure 125 - Topcon's Positioning Zone Laser Transmitter - *Topcon, Inc.*

The 3D-GPS+ System is a commercially available product developed by Topcon. It is used to locate the variety of positioning within a three-dimensional grid of the working site. Working in conjunction with the computer model, this system can strategically position the unique placement of the parts inside the computer generated model in conjunction with the actual site.

Functionally, the Topcon's 3D-GPS base station is set up on a tripod directly over an existing point on the actual construction site corresponding with the computer model. It remains unchanged in this location for the duration of the job and the base station is readily on hand to receive and send precise position corrections to and from the machine. Unlike traditional applications of using lasers as locators that require to be repositioned as the job progresses, this new GPS technology does not need to change location from its initial placement; therefore, common errors associated with the transferring of data from software to machine are minimized if not eliminated.

In addition, with the advancement in the next generation of 3D measuring devices that are currently in development in the area of metrology, the on-field measuring methods within the MPPS can become accurate and the possibility for analysis and understanding of the entire construction site will truly be infinite.

6.1.4 Working Site

This factor remains the same as in all of the site condition criteria that are required within the MPPS. As mentioned in chapter 3, the working site in this case is defined as a controlled area that is free from obstructions of any kind for openly autonomous movements. Although a selective number of groundwork might be necessary; however, unlike previous versions, the six-wheel design of this machine is capable of operating in particularly rough terrain due to the flexibility of its suspension system. Therefore, even if some site preparation might be required, complete overhaul and flattening of the site might not be necessary.

CHAPTER 7:
AUTOMATION AS A DESIGN TOOL

7.1 Automated Architecture

Figure 126 - SMART building system - *Shimizu Corporation, Japan*

Automated construction technologies have always been researched and developed from a construction or an engineer's point of view. However, when considering adapting design principles to robotics or automated construction systems, there are several possibilities for optimal usage of the automated techniques[10]. Alteration of the current automated system to become a design tool that designers and architects can use to create is a very logical development. Nevertheless, to be able to turn an automated system or a construction robot into a top-down approach from a designer's end, instead of the usual bottom-up technique from a construction's end, is not only difficult to

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[10] This is in reference to a paper called "Designing for Automated Construction" written by A. Scott Howe while at the Kajima Corporation.
- For more information: http://www-personal.umich.edu/~ashowe

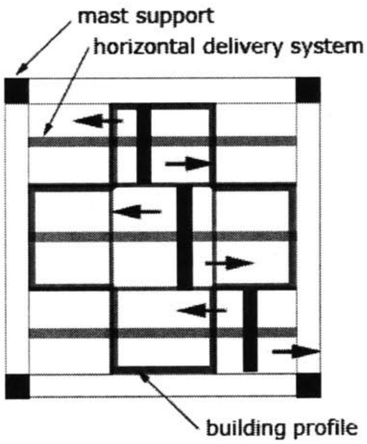


Figure 127 - An evenly distributed design configuration and the horizontal placement units are placed accordingly

accomplish, but also at the current state, technologically impossible.

However, the SMART system designed by Shimizu Corporation does have a very minimal ability to adapt to unique designs. The distinctive feature of this particular system is that the trolley hoist of the horizontal delivery system can be configured during the initial setup stage to correspond with a fairly unique building design. Figure 113 and 114 shows two different building profiles, however, the design and configuration of the gantry system and horizontal placement of the units are adjusted to conform to the specific building footprint.

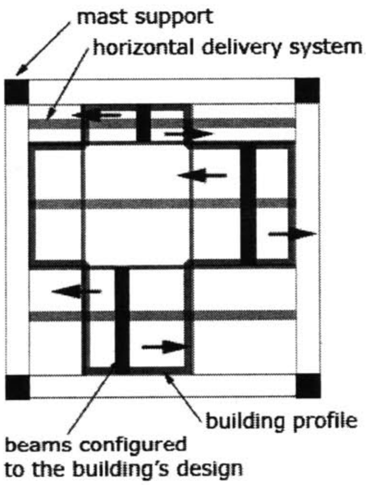


Figure 128 - A unique distributed design configuration and the horizontal placement units are configured accordingly

Therefore, to be able to develop a system that can act essentially as a tool for architects and designers to use when designing is of the utmost important. Regrettably, buildings that are designed for the automated techniques today are fully controlled, modulated and simplified because the technology forces it to be.

However, if there was a system that can change the ideology of making straightforward buildings to a more unique process of constructing complex structures. It will not only alter the inter-working and collaborative relationships within the design, manufacturing, and construction industry, but it will revolutionize and lead the way for the next generation of construction process.

7.2 Keep Up and Press Forward

The next step in the research and development of automated construction technology will involve many factors. First and foremost, it is not only necessary to keep pace with the

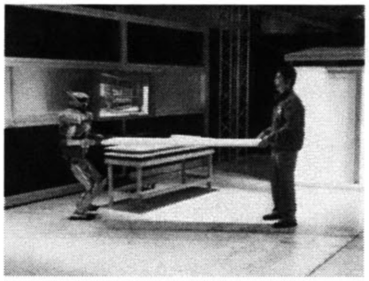


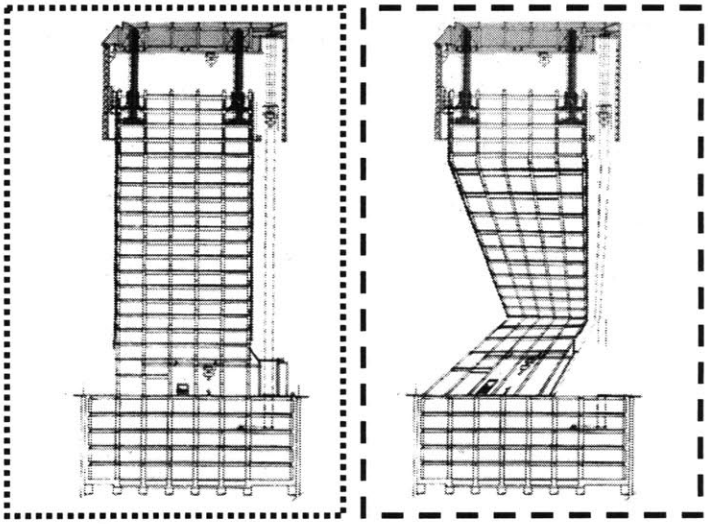
Figure 129 - Humanoid robotics platforms developed in HRP (Humanoid Robotics Project) - *Sponsored by METI/NEDO - Honda R&D*

rapid progression of robotics and artificial intelligence technology, but it is also critical for designers and engineers within the construction industry to persistently press forward the advancement of construction techniques. Secondly, the next-level development of advance complex motion control systems, mechanical drive systems, programming software, and sensor technology are just a few particularly imperative criteria that are crucial to the assembly operations and feedback information that is required for a smarter robot or system.

The design and development of robots alone combine several diverse disciplines. With the emergent of automated construction robot or system technology, it is essential that there is a need for inter-disciplinary training and education since automation requires many unique mixtures of multifaceted specialists. Prominently, autonomous or not, robots demand knowledge from those in mechanical engineering, electrical engineering, electronics, computer science as well as those in manufacturing and production engineering departments. Adding automation and artificial intelligence to the mix, unique specialist and scientists in the area of physics and mathematics are not only beneficial, but are very much necessary.

7.3 Speculation of a New Process

It is understandable that the automated process is particular good and efficient at creating rectangular or orthogonal buildings. However, what if there was a system or a series of robots that can construct irregular or non-orthogonal buildings such as Gehry's architecture? Let's revisit the 3D printing process as a technique. It has the capabilities to produce prototypes of designs rather rapidly. When doing so, it does not factor in the differences between the geometry of what is being produce. Whether it is a square box or a curve shape volume, it treats and produces both geometries in the same manner and the cost of both geometries are equal, as long as they have the same area of cubic volume.



EXISTING SYSTEM **IDEAL SYSTEM**

Figure 130 - Adaptation of the SMART system. On the left, the actual SMART system by Shimizu Corporation. On the right, a proposed design oriented system.

Is it then possible to take the same approach of constructing buildings? What if there was a system that takes in the consideration of reducing the overall cost, shorting the construction period, providing superior products, and offering a more productive and safer working environment, that cost the same when constructing a complex or simple geometry building? How would a system or a robot of that nature work? What type of information or intelligence does something like that need? What consideration does it require in terms of mechanical structure and associating actuators and sensing devices? The answer to these questions can possibly be found in technologies that have already been developed.

With every new development of advanced technology conventional boundaries have to be crossed and new methodologies will emerge. Particularly at the current rate of advancement, it is very easy to overlook and disregard current technology as something adaptable. Therefore, if we want to create something new, we need to analyze what has been created in the past. It is in our nature to think that in order for us to be innovative we have to generate novel ideas and reinvent the wheel. Although modifications to the wheel itself are often necessary, understandings of the wheel's origin and its overall purpose are especially significant.

When dealing with automated technology, it is a well known fact that even the act of automating the simplest task can be virtually impossible. Just as Marvin Minsky once wrote, "we can hardly expect to be able to make machines do wonders before we find (out) how to make them do ordinary, sensible things." Therefore, a fully-controlled automated construction environment might not happen any time in the near future. However, an environment that can offer more effective, productive and safer working conditions is almost here, and before long, it will revolutionize the methodologies and techniques of the design and construction process.

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APPENDIX

Appendix A: (Interviewed and Questioned)

A.1 PROFESSIONALS

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Appendix B:

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B.1 TABLE OF FIGURES