



Designing for Automated Construction

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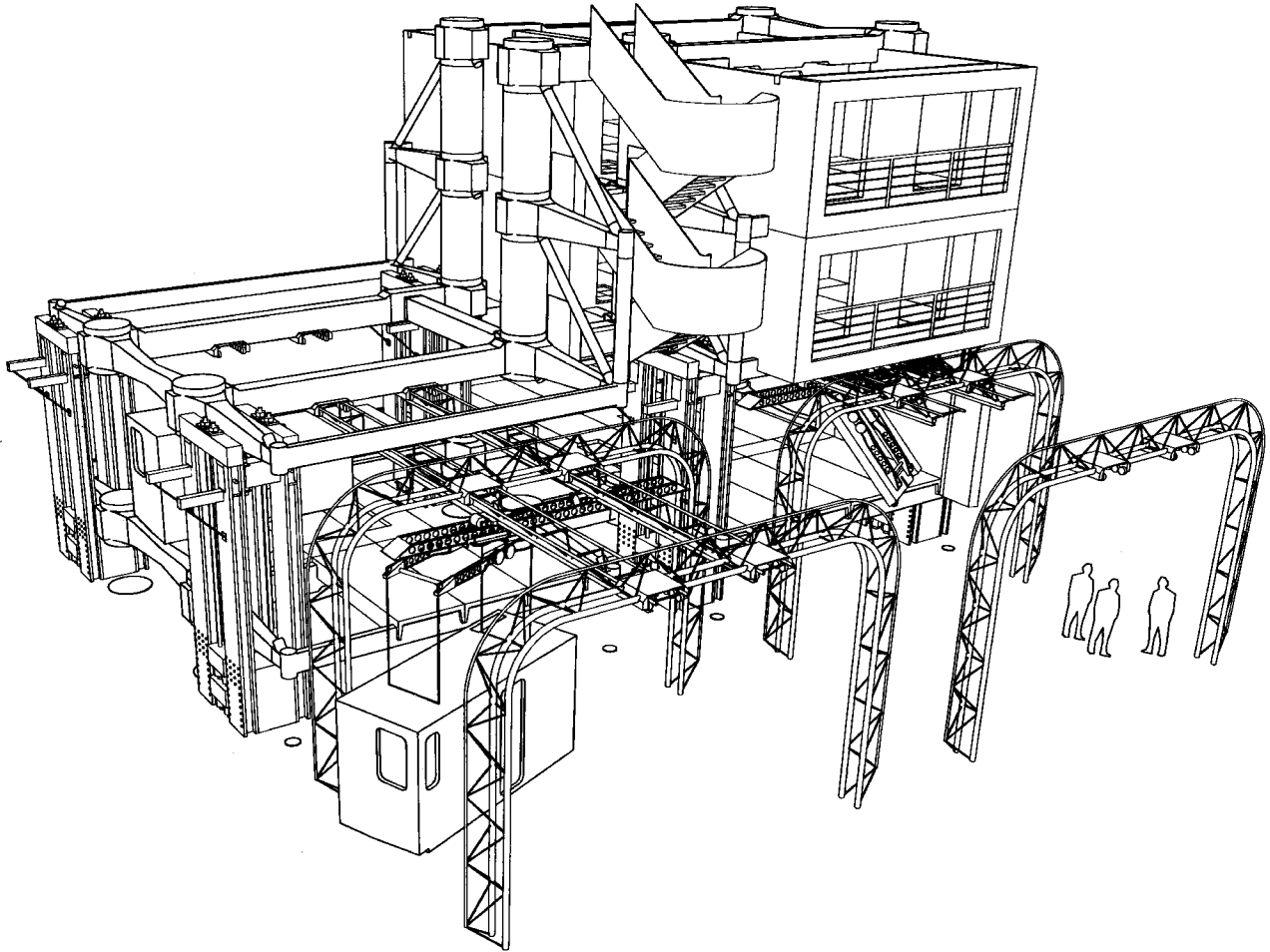
Introduction

Automated construction research can be divided into four main areas. The questions could be asked, first, what are the advantages and disadvantages of automating construction processes? Second, what are some of the implications of incorporating automated features into a building? Third, what are limitations and problems that must be overcome by robots and construction machines (some specifications for designing robotic systems tailored for architecture)? Fourth, and last, if certain optimizations can be achieved through automation, what would a likely tool box of principles or rules-of-thumb consist of, which designers could structure architectural concepts around? The first and second areas address justification and feasibility, and the third and fourth areas cover design.

In part I of this paper, the state of the art of automated construction will be explored using exemplars of papers and actual projects. Many of the questions asked regarding justification and feasibility have been discussed in the exemplars presented in this section.

Part II will be devoted to the design of a research programme which seeks to address topics related to designing robotic systems for construction, and developing overall design principles.

Part III will present a partial report of the research carried out according to the programme, and introduce a concept automated construction system designed according to the principles derived from the part II investigation.



PART I: STATE OF THE ART OF AUTOMATED CONSTRUCTION

Background

Architecture can for the most part be described as the creation of singular artifacts addressing case-specific needs for shelter. Architecture is not generally mass-produced, but is usually one-of-a-kind. This is one of the main reasons that the construction industry has been slow to adopt new manufacturing technologies which naturally come out of competitive mass production processes. In fact, there are many building construction methods and technologies in use today, such as masonry and rough carpentry, that can be traced back hundreds and even thousands of years.

Since the advent of the Industrial Revolution, architecture has seen slow, evolutionary progress in improvement of construction methods. Because of the one-of-a-kind nature of buildings, it has not been applicable (except in rare cases) to use mass-production techniques in construction. Still, improvement in the development of construction machines and tools has seen much progress, and the overall attempt to gradually adapt the new technologies to traditional building methods is taken for granted.

In recent years, however, another trend is emerging in parts of the construction industry which have to do with revolutionary changes in construction technologies. Instead of adapting new technologies to traditional methods, altogether new methods, conceived with the new technologies in mind and tailored to architecture, are being explored. One of the most dramatic of the new methods is automated construction, or the process of constructing (or manufacturing) buildings using robots and automated construction machines.

With the use of altogether new methods of construction, our conception of how buildings go together will change. A knowledge of the new construction methods may influence the formulation of design concepts and encourage conscious effort on the part of architects to design for efficiency of manufacturability. "Design for manufacturability" could provide a healthy constraint around which creative designers can establish the aesthetic of the building in addition to pure function, much the same way building codes can provide healthy constraints which influence the design.

Automated construction technology will be explored through five topics: design, materials handling, application to traditional methods, progressive methods, and actual implementation & development.

1. Designing for Automation

The majority of automated construction research and development has been bottom-up, from the construction / engineering side rather than top-down from the design end. The reason for this is obvious, since construction processes have no clear relationship with clients and users but everything to do with the production of the building. For this reason there are few papers available that address design for automation. When automated construction practices become more prevalent, it is assumed that more designers and architects will begin to address the issues that face their profession.

As an exemplar, Bridgewater (1993)¹ has discussed design considerations for automated processes. Two levels are described at which designers need to incorporate ideas of automation into their design concepts: component level and machine level. Neither one of the levels advocate radical changes in designs themselves, but only in how the building is to be constructed and detailed. Essentially, designers need to consider the manufacture of larger parts in factories that can be assembled quickly on the site by appropriate construction machines.

At the component level, Bridgewater explains the concept of "strong axis of assembly". Building construction usually involves assembly of components in a vertically downward direction. This is naturally due to gravity, and becomes what is called the strong axis of assembly. When the strong axis is identified, various tricks can be applied which simplify the assembly process and encourage ease of constructability. Those include beveling of joints and guides, Cartesian orientation with minimal rotation, wiring harnesses, and snap-fit joints.

At the machine level, different tasks must be contemplated in order to simplify the assembly process. Designers having a knowledge of the machinery available can detail construction of joints and consider material handling methods which are optimally conceived for automation technologies.

As stated earlier, papers available on the subject of design for automation are few. Though Bridgewater attempts to explain how designers should consider how buildings are constructed and detailed in order to optimize automated processes, nothing is said about rethinking the design concepts themselves for even greater optimization. In fact, this area is weak overall and can be viewed as a large hole in design for automation research. Part II of this paper will delineate a research programme designed to partially fill in this hole.

When designing for automated construction, the architect must remember that the range of area within which a robot can reach or perform work is called a work cell. Work cells are different depending on the design of the robot. In building construction, the multiple tasks required to complete the construction must be matched with work cells of corresponding appropriately designed robots. It may not be sufficient to use off-the-shelf robots for all tasks, but the design of construction machines in parallel with the building may be appropriate at times. For this reason it may be critical that design concepts of buildings to be constructed using robots and construction machines be sensitive to work cells and automation concepts.

2. Materials Handling

In considering new construction processes utilizing automated construction, development of single-task, single-function robot in isolated environments or work cells is insufficient. A whole issue covering the handling of the materials and building components emerges, which seeks to provide smooth flow of the machinery and increase overall construction productivity.

Skibniewski and Wooldridge (1992)² discuss the use of material handling in high-rise construction. In material handling, building components are manufactured in factories, shipped to the construction site where they are temporarily stocked, and then delivered to the construction mechanisms for assembly into the building. Various automation technologies are utilized in the process, including Automated Guided Vehicles (AGV's), Automated Storage / Retrieval Systems (AS / RS's), robotics, and automatic identification. In automated construction these technologies are applied to the three major tasks of building, warehousing, and manufacturing, and material handling systems must provide the link between the three.

Not all the processes involved with material handling can be automated as of yet, for the delivery of assembled components from the factory to the site, and from raw materials to the factory still require human intervention. Nevertheless a major portion of material handling can be automated. Skibniewski and Wooldridge describe the use of autonomous fork lifts, conveyors, automated lifts, and AS / RS warehousing in the construction of high-rise buildings in Japan. These systems used together make up a materials handling work cell, which physically overlaps all the work cells of the various robots and construction machines to the point that appropriate materials are delivered to each properly and on schedule.

3. Traditional Methods

A great majority of the work going on in automated construction research is in thinking of ways to apply the technology to traditional building methods. While there are a great many problems

that need to be overcome in order to develop usable automated tools, studying possible applications to traditional methods is necessary because they are the most familiar to us.

Bernhold, Abraham, and Reinhart (1990)³ advocate the application of automation technology in an evolutionary rather than revolutionary manner. In spite of the fact that buildings tend to be unique and prototypical, a careful analysis reveals that uniqueness can only be used to describe the condition at the higher levels of construction function: organization, project, and activity. Basic levels of function such as process, task, and motion are largely repetitive in nature, which is amenable to automation principles. Bernhold, Abraham, and Reinhart discuss flexible manufacturing system (FMS) concepts, meaning the use of highly adaptive machinery that can handle a variety of tasks rather than specialized equipment. These adaptive devices can be programmed to build everything from a brick wall to finish siding.

The work of Leonhard Bernhold was chosen as exemplary not only because of the concepts advocated in the FMS paper, but also for other work which attempts to apply automation to traditional building methods. This work includes the development of robotic masons, bridge painters, and excavation tools.

Another exemplar of the automation of traditional methods is Roozbeh Kangari⁴. Kangari has researched the potential of robotization of individual tasks required in construction, assuming that the feasibility of automating the entire construction site would be dependent on need and would occur gradually. Tasks were rated by difficulty, repetitiveness, and safety among others.

4. Progressive Methods

Instead of adapting automation technology to traditional methods, some research is being conducted which seeks to develop entirely new methods for construction. These methods often use assembly techniques which are optimal for use in automation or attempt to apply as much of manufacturing technology as possible by finding ways to mass-produce building components. The new methods often fall into two categories: modular construction and kit-of-parts building systems. The two categories overlap and can be thought of as being the same, but in this paper a differentiation is made by defining modular construction as being oriented from a systems level downward, and kit-of-parts as being oriented upward from an elemental level. Both of these methods have superb examples of development and implementation including the work of architects over the years, such as Fuller, Kurokawa, Foster, Piano, and Rogers, and many have hinted at the use of automation in manufacturing of components. Still, few have actually made the connection, which is required for consideration as an exemplar in the scope of this paper.

Kurita, Tezuka, and Takada (1993)⁵ report about the development of a three-dimensional modular unit construction system tailored to the use of automated construction. Large building block components are assembled in a controlled factory environment (whether on site or off is irrelevant at this point) and shipped to the site for assembly.

Bini (1994)⁶ is an exemplar of kit-of-parts development for the purpose of automated structure assembly. New space frame configurations and structural systems have been developed which assemble easy and lend themselves toward automation.

5. Implementation & Development

Automated construction techniques that have been fully implemented appear to fall into three major categories. First, collections of function-specific robots that work independently of each other, whose work cells are not necessarily laid out in a systematic way. Second, robotic systems which form a systematic "factory" that is stationary or fixed in the context of the site. Third, robotic systems which form a systematic "factory" that moves itself along as it completes portions of the building.

All of the examples in this paper are Japanese in origin. As we have seen so far, considerable research has been conducted in the United States, The Netherlands, and other countries but most of it has been at a university or research organization level. The majority of actual implementation has been in Japan. One reason for this is because of Japan's research infrastructure: large corporations conduct the majority of research under the encouragement of the Japanese Ministry of Construction⁷ and Japanese Ministry of International Trade and Industry⁸, and have the funds and will to bring ambitious projects to reality.

The first category covers those robots that have been developed for inclusion into manned construction sites, which do those jobs which repetition, labor, or safety needs make expedient. These machines have mostly been developed as a way of adapting automation techniques to traditional building methods. In addition, the first category includes robots and machines which are not necessarily part of construction but may have some function to do with the maintenance of a building along its entire life. As an exemplar, Taisei's exterior wall painting robot⁹ can be cited. On a high-rise building (Shinjuku Core building in Tokyo, Japan), vertical gaps at each column line that run the entire height of the building contain hidden rails. The painting robot is positioned into any two of the rails and automatically moves up or down the entire building facade doing its job without assistance.

As an exemplar for the second category, Kajima Corporation's AMURAD system¹⁰ will be discussed in this paper. AMURAD sets up a stationary factory on the building site, with fixed

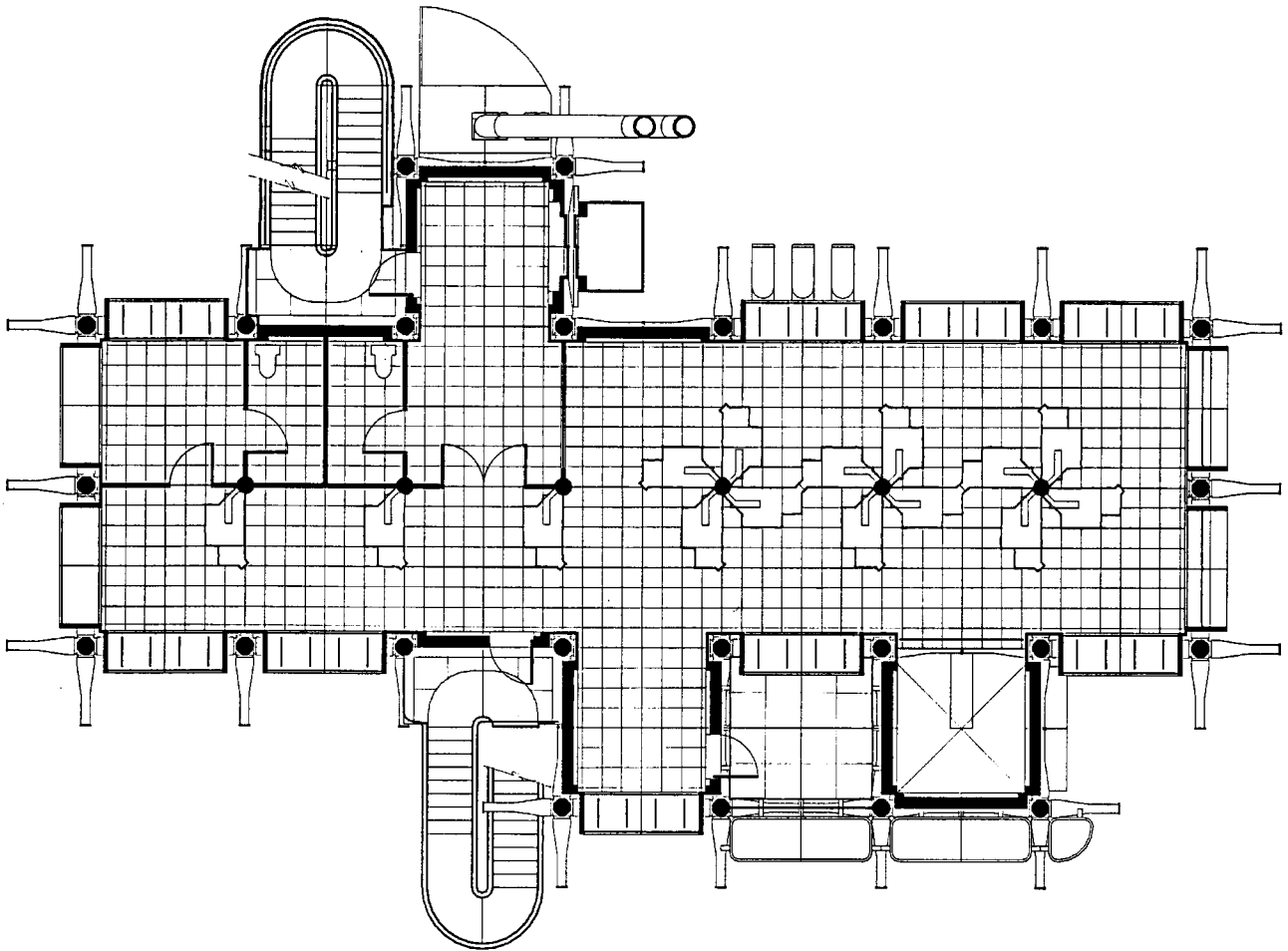
material handling routes that deliver pre-manufactured building components to the robotic system. The factory is set up to automatically assemble one entire floor at a time, and to jack the floor up one level when it is finished. As a result, a finished high-rise building is "extruded" out of the site. Upon completion of the building, the ground-level factory is disassembled.

In the third category, all of Japan's "big 5" construction firms (excluding Kajima) have some sort of implementation. The firms are namely: Shimizu, Taisei, Takenaka, and Obayashi. In this paper, Shimizu's SMART system¹¹ will be cited as an exemplar. The SMART system begins with a small core structure (which will become the building's core) being constructed conventionally to the height of a few stories. A platform the size of an entire proposed floor is attached to the top of the core. The platform contains a factory which proceeds to automatically assemble the entire ground floor, and in parallel constructs another level onto the core structure. When the ground floor is complete, the entire factory platform

automatically jacks itself up (using the core structure) one level and repeats the process with the second floor and so on. Material handling is done using automated lifts located in the core structure, where factory assembled components are delivered to the ground level and are automatically delivered to the factory. In effect, a finished high-rise building is "extruded" by the factory as it jacks itself up floor by floor. When the building is finished, the factory is disassembled and removed from the top of the building.

Part I Summary

Automated construction appears to be a trend that will stay. Though revolutionary strides are occurring in some corners of the industry, overall evolutionary changes toward automation are taking place universally. Research and development has mainly been from the bottom-up where engineers and construction management have direct influence over the construction process. Top-down approaches from designers and architects are still few and not sufficiently covered.



PART II: A RESEARCH PROGRAMME FOR DESIGN TOPICS IN AUTOMATED CONSTRUCTION

Background

In order to optimize the use of automated technology, it is important that design principles based on the technology are considered. Where most of the current research and development has been initiated from a bottom-up approach by engineers and construction managers, it may be advantageous to balance that with top-down theoretical approaches initiated by designers, architects, and researchers. Researchers can use various approaches to discover rules-of-thumb and general knowledge from which designers can draw from. Architects and designers may use automation as a theme or concept whereby the structural, functional, and aesthetic components of the building may be derived.

The research programme proposed in this section is devoted mostly to design principles, covering overall volume and space design as well as joint and detail design. It is hoped that the results of the research will provide valuable information for the design of flexible component-

based building systems which can be assembled with robots and automated construction machines.

The proposed research will be divided into two parts. 1) A theoretical research programme for the purpose of deriving a shape grammar that will provide a standard for both building volume generation and robotic work cell configuration for an orthogonal building system. 2) A simulation research programme for understanding component connections and robotic manipulation.

1. Theoretical Shape Grammars

It is assumed that an indefinite number of shape grammars that optimize the use of automated construction technologies can be derived for orthogonal or non-orthogonal buildings depending on the proposed structure, function, and aesthetic of the building. In the research proposed in this paper, however, and for the purpose of devising a guide for the design of volumes and spaces, an exercise deriving theoretical shape grammars for an orthogonal

building will be conducted. The purpose for deriving a grammar would be to provide a set of guidelines for allowed or disallowed space adjacencies, and generate rules for individual component shape. Also, structural requirements for the pre-engineering of individual components and hints about their potential interface with robotic construction systems can also be derived. The following assumptions will be used in the derivation of the grammar:

- 1) Primarily four types of spaces will be considered: user space, exterior space, circulation space, and core / service space.
- 2) Spaces and volumes are three-dimensional and can be situated adjacent to each other or stacked to create multiple floors. Stacked spaces can consist of any one of the four types regardless of the nature of the space above and below. Horizontally adjacent spaces can also consist of any one of the four types.
- 3) Large spaces can be horizontally adjacent to small spaces and do not need to be the same width. Likewise, large spaces and small spaces can be stacked and do not need to be the same width.
- 4) Circulation spaces must conform to legal egress and exit requirements.
- 5) Core / service areas must adequately serve the needs of the building.
- 6) Structural systems must adequately transfer the loads of the building to the foundation system.
- 7) Robotic construction systems must have work cells that are large enough or flexible enough to construct large or small spaces consisting of any of the four types.
- 8) Robotic construction systems must have work cells that are potentially expandable or automatically relocatable for indefinite horizontal building growth, as well as indefinite vertical building growth.
- 9) Robotic construction systems must include automated materials handling systems whose work cells overlap all other work cells as required.

In order to derive a grammar based on the assumptions, it will be necessary to produce a systematic set of rules that allow for all the requirements in a consistent sort of manner. For

example, the assumption that the structure adequately transfer building loads to the foundation system might allow large spaces to be stacked on top of small spaces, but could prove difficult the other way around. If in the structural, functional, or aesthetic design of the building it is necessary that small spaces be stacked on top of large spaces, pre-engineering of large-span structural components enough to support intermediate structure would have to be taken into account.

In another example, if all four types of spaces can be stacked regardless of the type of space located above or below, potentially a four story building could have exterior space at the ground level, user space at the second floor, exterior space at the third floor, and user space at the fourth floor.

When the shape grammar is derived, decisions about the robotic building system work cells must be made. Perhaps a robotic system builds several structural bays at a time, jacking itself up after completing each floor and finally relocating itself horizontally & vertically in order to position itself for the construction of the next set of bays.

In all of these examples, shape grammars would define what type of configurations were allowed or disallowed. Space generation rules would effect component design, placement, and requirements for structural pre-engineering. Grammars governing limits on robotic work cells may effect building configuration. Space generating grammars conforming to robotic work cells, or work cells conforming to space generation all have an effect on the overall building design.

2. Automated Construction Simulation

In order to understand the implications of using robots for building construction, proposed is a simulation using a real robot to construct a model building. The simulation will provide a testbed for component connection concepts, component / manipulator relationships, and robot control. The simulation will test the following assumptions:

- 1) Through various circumstances and influences the robot's movements may be imprecise. The design of the building components can be robust enough to correct such errors, by the use of bevels, guides, and other devices.
- 2) Components can be mountable and demountable for reuse. No permanent constructions or installations.
- 3) Components can have mechanisms or effectors built into them which function as self-locking joint connections. The mechanisms can be activated and deactivated by the robot's manipulator to facilitate ease of construction or disassembly.

- 4) Components can be designed to have maximum flexibility in placement such that a variety of building configurations can be accommodated. Building component placement is only limited by the extents of the robot's work cell.
- 5) Robot can be completely autonomous in the construction sequence such that human intervention is not required. Construction sequence can be initiated locally or remotely.

In order to test the assumptions, a model construction site simulation is proposed. The site will be modeled on a table which lies within the work cell of an RTX industrial SCARA¹² robot. The RTX has six degrees of freedom which facilitate the placement of objects at any specified orientation, and at any specified location within the work cell. The RTX has a gripper-type manipulator with two hinged facing contact plates. The RTX can be controlled manually through teleoperation or autonomously through pre-programmed sequences consisting of an unlimited number of joint commands.

To simulate the building, a kit-of-parts model building system will be designed which has two different types of components: wall panels and floor / roof panels. The components will connect to each other by means of plug-in, self-locking mechanisms which disengage through pressure from the robot's gripper contact plates, and re-engage when the pressure is released. The mechanisms within the components will be spring loaded into the locking position and will act as a "seventh" joint when coupled with the robot's manipulator. The components will be manufactured from Plexiglas in order to facilitate ease of re-design and re-manufacture.

Foundation components will not be produced within the scope of this simulation. Instead, a ground plate will be manufactured which has the same plug-in joint receptors that the components have. The plug-in joint receptors will be located in such a way that components can be plugged-in in a variety of positions and orthogonal orientations.

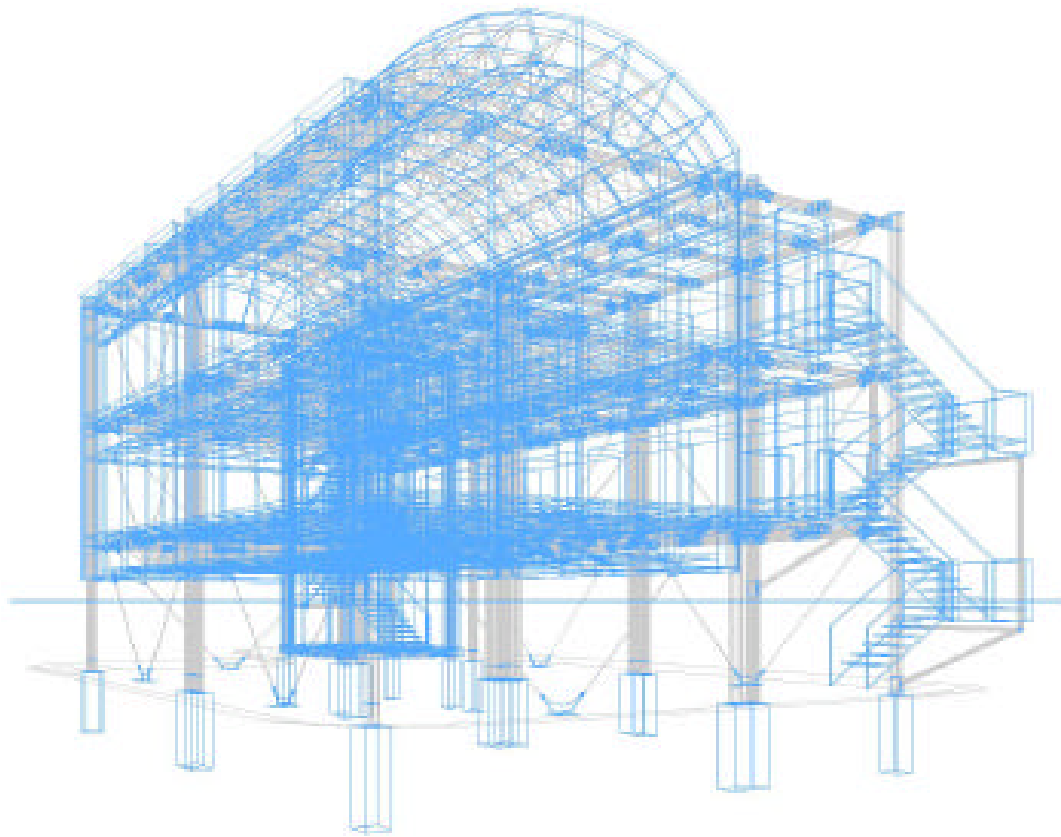
Control will be facilitated by a small computer located adjacent to the robot, which will execute either real-time teleoperated commands or pre-programmed sequences of commands. Teleoperation or pre-programmed sequence launching will be facilitated by a keyboard attached to the computer locally. Pre-programmed construction sequences will also be launchable over the Internet from a World Wide Web page, to demonstrate complete autonomy and remote control.

The simulation will be conducted by first constructing a small model building by teleoperating the robot. Second, the building will be dismantled using teleoperation. Third, the building will be constructed again from pre-programmed joint control sequences, without human intervention, initiated locally. Fourth, the building will be dismantled using pre-programmed joint control sequences initiated locally. Fifth, the fully automated construction sequence will be initiated from a remote location over the Internet. Finally, the fully automated dismantle sequence will be initiated from a remote location over the Internet.

Through this simulation it is hoped that the five assumptions can be tested and demonstrated. It is also hoped that through the process of design & re-design of the components during the process of facilitating the simulation that valuable insight and experience can be obtained which lends itself toward more efficient detail design. In using the model components, it is hoped that scaleable principles for full-size implementation can be derived, without the production costs associated with full-size mock-ups.

Part II Summary

Using a combination of theoretical and simulation research approaches, it is hoped that a general understanding of how the use of automated construction technologies affects the design of the building can be attained. The two approaches represent a micro and macro view of the design problem and are expected to provide valuable insight on issues ranging from detail design to space and volume manipulation.



PART III: RESEARCH REPORT AND DESIGN IMPLEMENTATION

Background

In part II a research programme was proposed for exploring principles related to designing for automated construction. This section will be divided into three parts: 1) a report covering the results of the simulation research, including resulting design related guidelines, 2) a partial description of a theoretical shape grammar based on automated construction principles, and 3) an example implementation of how the design principles and shape grammar can be applied to an actual design concept.

1. Simulation Research Report

The first step in preparing for the simulation was to gain a familiarity with the RTX robot, which included an understanding of the robot's work cell. Using "teach" mode¹³, the robot was manipulated via teleoperation through the computer. Various wooden blocks were grasped, stacked, and unstacked. Simple Pascal routines were written for autonomous operation of the robot, and formulas derived for converting controller coordinates of each joint into robot coordinates.

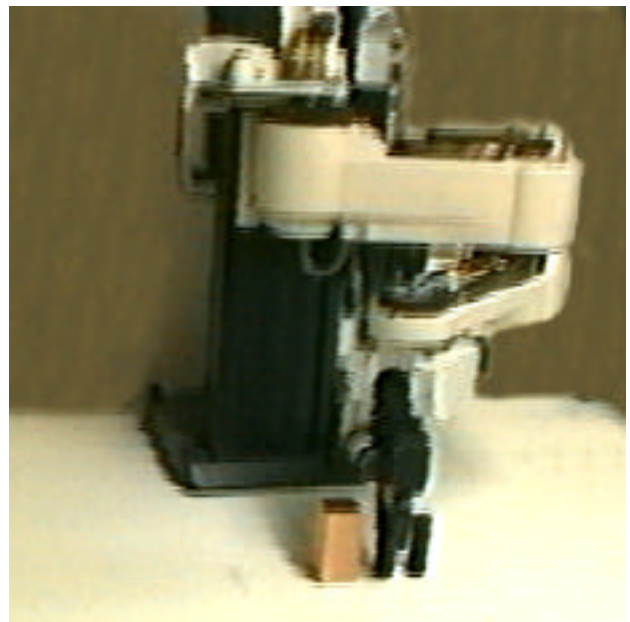


Figure 1: RTX robot

COMPONENT DESIGN: When the overall functions of the robot and the limits of its work cell were understood, the simple model component building system was designed. The components were manufactured entirely out of Plexiglas. It was

decided that the kit-of-parts would be designed around a three-dimensional grid of 10cm on center, where wall panels would center on the grid in the X and Y directions, and floor / roof panels in the vertical or Z direction. Where the lines of the grid met, plug-in joints or connector receptacles would be placed.

It was decided that the joints were to consist of a passive connector receptacle coupled with an active clasp mechanism. Each component would have both passive and active mechanisms located respectively on the receiving end and installing end. In other words, a wall panel would have an active mechanism where it was to be plugged into the floor, and have passive receptacles located elsewhere for receiving the active mechanisms of other wall or floor panels. The location of these passive and active mechanisms would together coincide with the intersections of the three-dimensional grid lines.

The nature of the passive receptacles were designed early. It was decided that they were to consist of a simple hole 2cm in diameter, where active mechanisms would be required to latch into, in such a way as to prevent the components from pulling out.

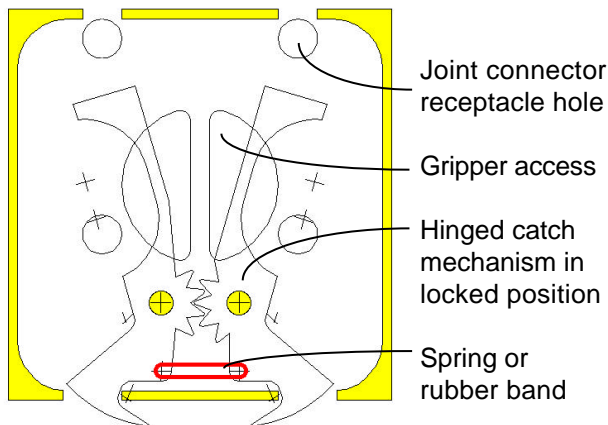


Figure 2: Wall component diagram

A Plexiglas plate measuring approximately a half a meter square, with holes drilled at 10cm on center in the form of a grid, was fastened a few centimeters above the RTX's work table. The plate represents the building site, with potential joint receptacles ready to receive components in any location or orthogonal orientation on the grid.



Figure 3: Model wall component

Wall components were designed thick enough such that joint receptacle holes could be drilled into the top edges to facilitate "multi-floor" stacking. It was decided that the wall panels would be approximately 20cm square, with two joint mechanisms centered on the bottom edge and two receptacle holes centered in the top edge.

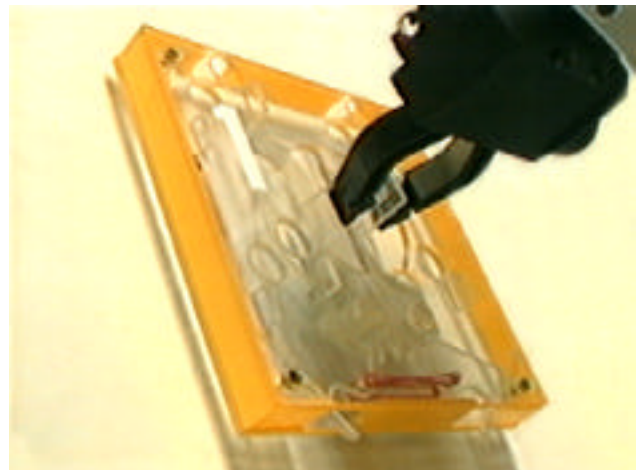


Figure 4: Disengagement of mechanism

The simulation research programme required that the joint mechanisms be continually spring-loaded engaged in the locked position, and only when pressure is applied by the robot's end effector would the mechanism disengage for installation or dis-assembly. For this purpose it was decided that a hinged mechanism with two opposing catches be installed within the panel, and that a large hole in the center of the panel would facilitate robot gripper access. The hinged catches

would be spring-loaded with a rubber band or spring in such a way that they naturally engage in steady-state. Installation of the panels would be facilitated by: 1) reaching into the access hole with the gripper, 2) grasping the hinged catches (which would both disengage the mechanism and provide a grasp hold on the entire panel), 3) lifting the panel into position above two receptacle holes, and 4) releasing the hinged catches to allow them to engage in the holes. The hinged catches swing from an out-of-the-way position into the holes until they lock back into place.

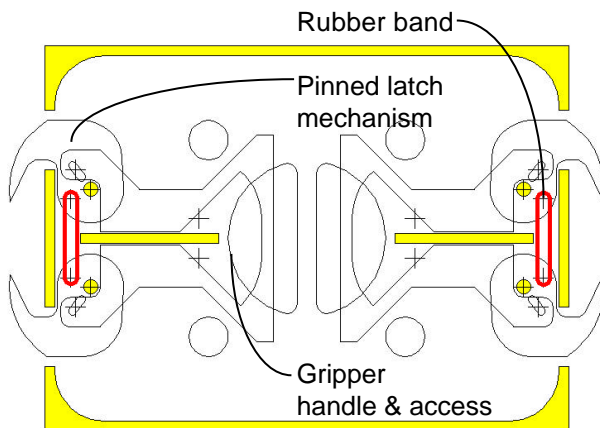


Figure 5: Floor component diagram

The floor panels were designed in a similar manner as the wall panels. Since the design grid was three-dimensional, 2cm diameter holes occurring vertically every 10cm as well, defining the floor panel thicknesses in the same manner as the walls. Rather than resting on top of the wall panels, each floor panel slides in between two wall panels and latches into the vertically oriented receptacle holes located near the top of the wall. When installed, the pattern of receptacle holes located in the top of the wall panels combined with those on the floor panel reproduce the same receptacle hole grid occurring on the floor below. This can facilitate stacking for additional floors.

In contrast to the wall panels, the active latching mechanism in the floors are pinned. In order to install, the gripper would disengage the pinned latching mechanisms by sliding the two handles inward and retracting the locking arms. Upon release, the locking arms would swing back into place and lock the floor panel into position.

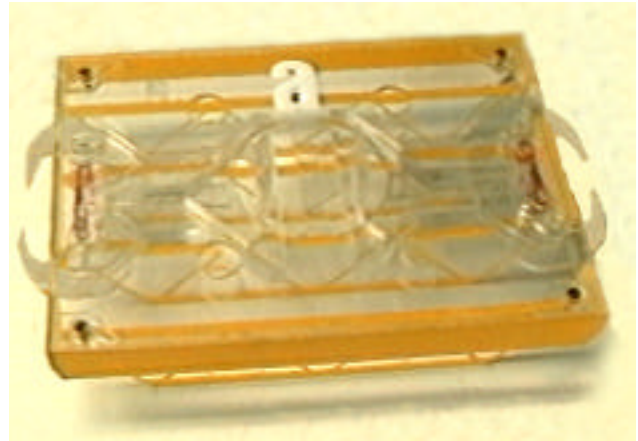


Figure 6: Model floor component

CONSTRUCTION SIMULATION: As per the programme plan, six simulations were conducted: construction and disassembly via teleoperation, construction and disassembly via pre-programmed autonomous operation, and construction and disassembly via remote autonomous operation. As of this writing an Internet connection has not yet been established, but is expected to be completed soon¹⁴.

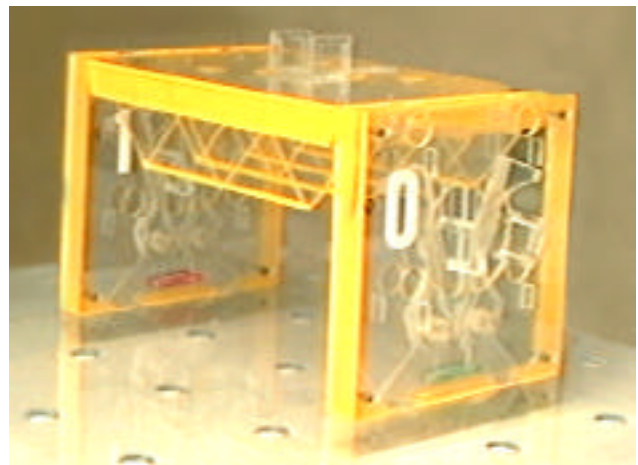


Figure 7: Constructed model

Although the simulation was a success, there were several problems encountered during the exercise that required design changes. Originally the gripper handles of the mechanisms were entirely within the face of the components. Also, the floor panels had no latching mechanisms but were equipped with straight protrusions that simply extended into the holes of the wall panels.

The first problem encountered was the narrowness of the space between the handles and the gripper access holes. During the teleoperation attempt it became clear that the gripper would not fit into the spaces. Through a series of redesign exercises, the problem was solved by attaching a plate to the latching mechanism handle which

extends beyond the face of the panel, giving the gripper plenty of room.

The second problem involved the straight protrusions on the floor panels. The protrusions would extend and push the wall panels apart if the positioning was slightly off. The problem was solved when the original configurations were redesigned to have active latching mechanisms as shown in Figure 5. The redesigned mechanisms would rotate into the holes to provide a secure catch.

Although the simulation consisted of assembling only two wall panels and spanning a floor panel between them, the model system was designed to allow for more complicated structures using many components. A total of eight wall panels and four floor panels were manufactured for future simulations.

DESIGN PRINCIPLES: The simulation was extremely valuable in that the redesign exercises provided a set of design principles that could apply to scaled-up kit-of-parts / automated construction systems. An essential list of some design principles is as follows:

- 1) Components should be designed to compensate for inaccuracies of robot position and orientation; bevels, guides, and snap-together connections are necessary for accurate assembly. All bevels and guides must be oriented in the strong axis of assembly. This principle will be coined as the “strong axis principle”.
- 2) It is advantageous to have a mounting mechanism in the building component itself, which either engages upon installation or is activated / deactivated by the robot’s end effector. This principle will be coined as the “seventh joint principle”.
- 3) Construction sequences should be planned in such a way as to allow the robotic systems to work freely and have access to the site; parts which will be buried under or hidden behind other parts should be placed first while there is still access. This principle will be coined the “assembly sequence principle”.
- 4) Design of grasp points on the component, as well as design of the nature of the robot’s end effector must be done in parallel with each other. The give-and-take of the design will depend on many factors such as ease of manufacture, component appearance, and transportability. Balancing heavy components can become a problem unless the lift points have been carefully

placed and designed. This principle will be coined as the robot / component “interface principle”.

There were other principles that were derived that were not seen as essential to the design but were felt to add to optimal construction practices and material handling performance:

- 5) For the purpose of compact transportation and accessibility, the stackable storage nature of components could hold importance in many situations. In the simulation, the original design of having mechanism gripper handles located entirely within the faces of the components allowed for compact storage stackability. Having to redesign with a protruding gripper plate, the stackability feature was necessarily sacrificed. This principle will be coined as the “stackability principle”.
- 6) Another principle relating to the “assembly sequence principle” concerns the path the robot takes from component storage position to install position. It is necessary that both the moving component or the robot do not collide with already installed components or other objects in the environment. In this simulation, paths were defined in Cartesian movements to allow plenty of room, but more efficient motions could be derived to facilitate optimum paths for speed and accuracy. These paths are mainly a construction problem, but careful thought during the design stage could improve manufacturability. This principle will be coined as the “path principle”.

The simulation consisted of constructing a model building using a kit-of-parts system. The robot used was a SCARA type arm with a gripper-type end effector. How the above six design principles up-scale into the design of an actual building and robotic construction system would be a critical issue. Literal up-scaling would mean having a 60 foot tall SCARA robot with a huge gripper-type manipulator. The rest of part III will be devoted to solving some of these problems.

2. Theoretical Shape Grammar

The research programme in part II called for the derivation of a theoretical shape grammar which could be utilized to generate spaces and robotic work cells. This section will introduce a partially derived shape grammar based on the programme. It must be noted that the shape grammar described in this paper is only one possibility of many, and that not all building types could appropriately function using this grammar.

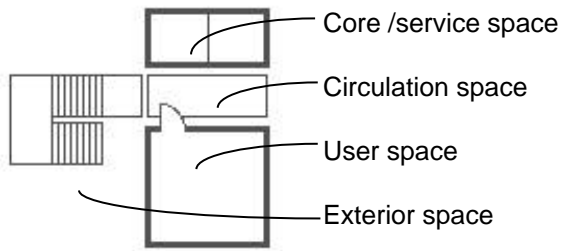


Figure 8: Space types

SPACE GRAMMARS: In the shape grammar, four basic types of spaces are addressed: user space, circulation space, core / service space, and exterior space. It was decided that a basic model arrangement of the spaces would be as shown in Figure 8, with circulation spaces functioning as a trunk and core/ service and user spaces opening off of it as required. Either of the three core / service, circulation, and user spaces can be replaced by each other and by exterior space if necessary, but this pattern stands as the norm.

The space arrangement in Figure 8 represents a single “bay” of the building. In the shape grammar it was decided that in addition to the spatial system, the bay size would correspond with both the structural system and the robotic construction system work cell.

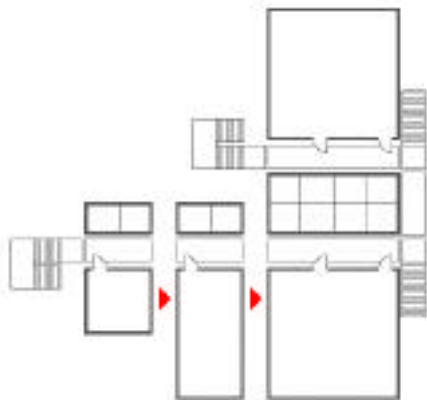


Figure 9: Additive bays

The bay size would have a maximum and minimum width, but would have an unspecified depth. Widths and depths can vary from bay to bay. Bays can be added together in an unspecified number, as long as egress rules are complied with. In addition, the basic space model can be mirrored such that two units have their cores back-to-back. Alternatively, two units can have their user spaces belly-to-belly to essentially create one large user space bounded by two sets of circulation and core / service spaces. Finally, a bay or set of bays can be set at right angles from another set of bays if

circulation and core / service spaces are arranged in a certain adjacency.

In the shape grammar, user spaces would be divided according to function and need by systematic partitioning systems, both actual and virtual. The internal functional size needs would be a determining factor for deciding bay width.

COMPONENT GRAMMARS: In addition to a shape grammar devised for space generation, another grammar for component shapes and interfaces can be derived which will support the overall grammar.

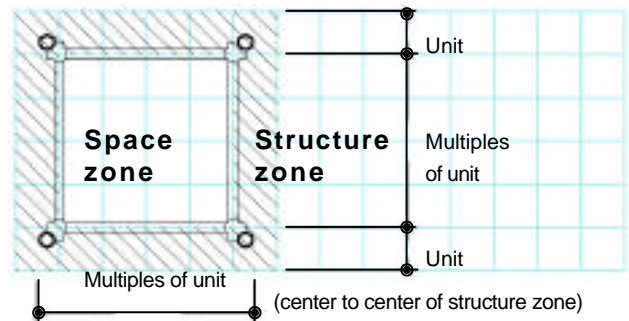


Figure 10: Space & structure zones

Architecture is essentially a collection of function-specific spaces. The structure and envelope conceived in the design process is for the purpose of containing those spaces. In this component grammar, the process for assembly of the structure has been given priority as well, and the concept behind the containment of spaces is therefore influenced. Figure 10 is a diagram of a single structural bay, showing space zones and structure zones. Two overlapping grids are utilized: the basic grid and structural grid. The basic grid is based on economy of material and transportability. The structural grid is derived from the basic grid. The structural grid consists of zones which are multiples of the basic grid in width, and define space zones which are also multiples of the basic grid.

When two bays are put together, the adjacent structure zones overlap, but the actual structure may not necessarily do so. In Figure 11 the structures of two bays are shown completely independent of each other. By keeping the structures independent, expansion joints, passive seismic connections, and automated construction principles can be facilitated. The building can be constructed a single bay at a time, optimizing the area that can be covered by the robotic building system work cell.

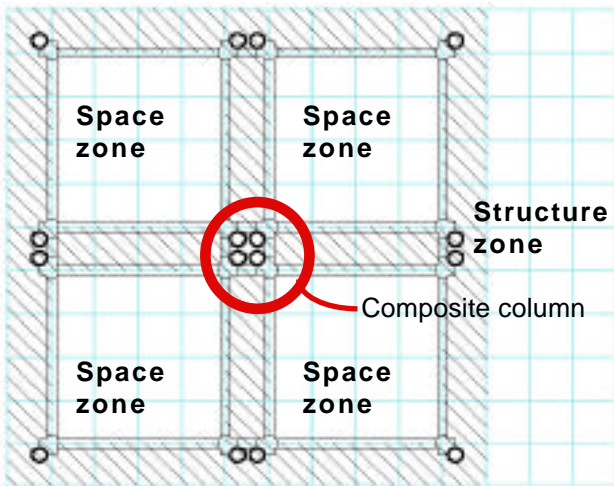


Figure 11: Adjacent bays

Using the automated construction concept, the building would go up a single bay at a time to an indefinite height (limited by the pre-engineered specifications of the members). The independent bay structures would be linked later (with either rigid or seismic expansion connections) to form composite columns in the overlapping structure zones.

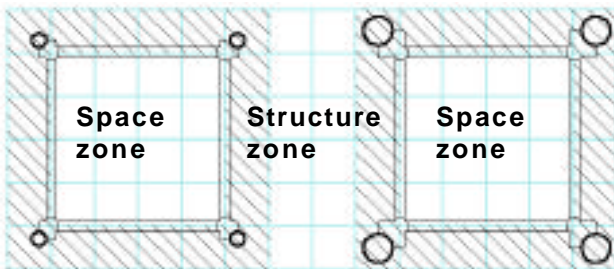


Figure 12: Alternate structure

Using the space-zone / structure-zone concept, various types of structure could be implemented as need requires. Single story buildings could be constructed with the same system as multi-story structures.

Figure 13 shows two adjacent bays with common structure zones. Since the structure zone is an increment of the base grid, continuous spaces can be facilitated with regular components. Wall panels, floor panels, and ceiling panels sized on the base grid would seamlessly connect the gap between the two bays. In this way a component shape grammar and overall space generation shape grammar can compliment each other.

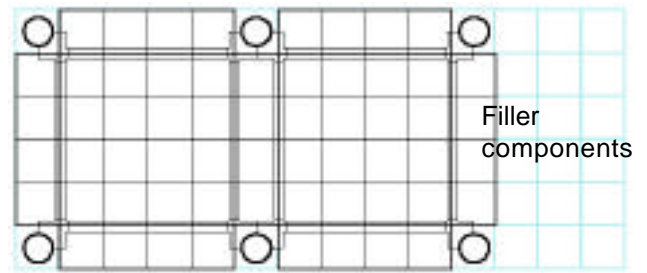
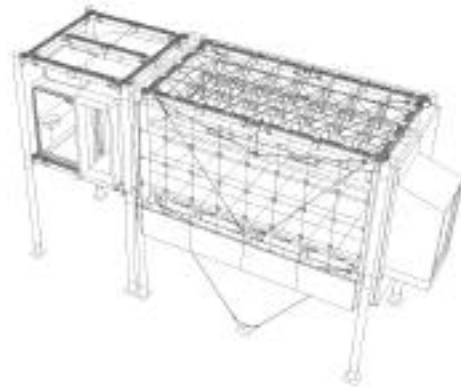


Figure 13: Continuous spaces

3. Design Implementation

In this final section of part III an example implementation of the six design principles and shape grammars will be discussed.



DESIGN PROBLEM: In order to design a kit-of-parts building system based on automated construction principles, an example design problem will be explored. The problem will be a 300m²+ teaching / training facility for a church, school, or business. In the context of the example it is expected that around 60 buildings a year will be constructed, with as many variations in design, materials, and aesthetics. Because of the large number of buildings to be constructed, it is assumed economically feasible to implement an automated building system.

In order to insure optimum flexibility of the kit-of-parts system, a series of prototypes will be designed. One of the prototypes will be a facility with 12 teaching stations, which can be combined into three larger multi-purpose rooms. In addition, restroom facilities, a small kitchen, a small library, two offices, and storage space will also be included in the building program.

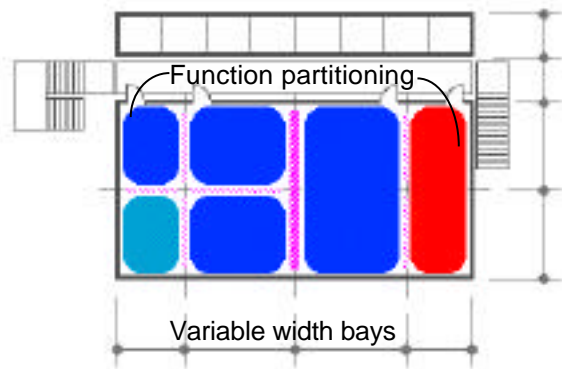


Figure 14: Space design

SPACE DESIGN: It is decided that the plan will basically be linear with several bays side-by-side according to the shape grammar. The various functions and spaces will be separated by movable partitions, according to variable width bays. The building will be two story.

In addition to the restrooms and kitchen, it is decided that the offices and library also be included in the core spaces, leaving the user spaces as openly flexible as possible for the teaching / training functions.

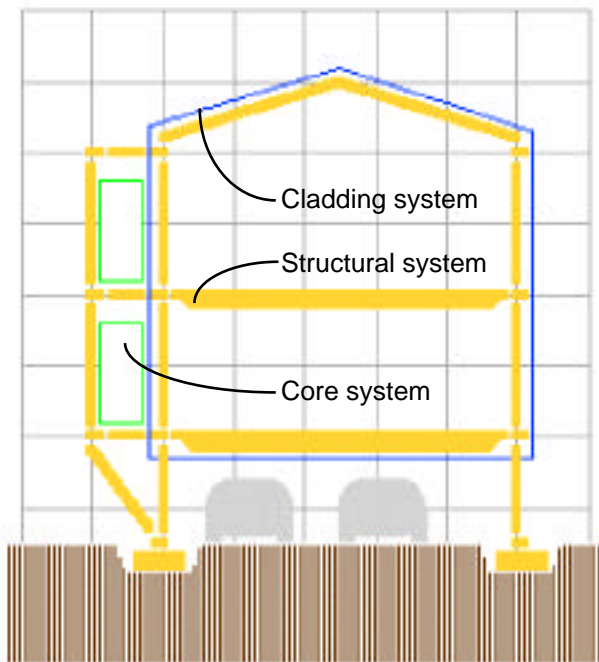


Figure 15: Component building systems

COMPONENT DESIGN: In the context of the problem, it is decided to use two main systems in combination. The user and circulation spaces will use a flexible kit-of-parts system sized on a base grid of four feet, and the core / service spaces will

be a system of function-specific pre-manufactured modular units.

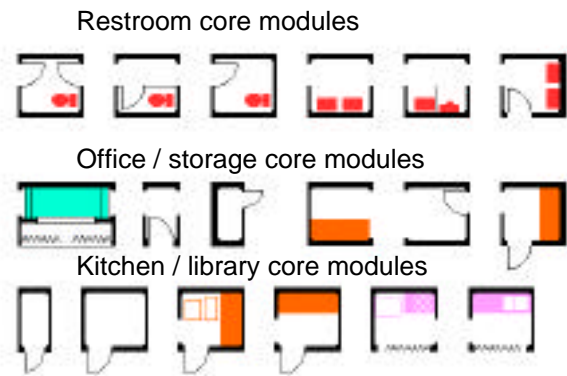


Figure 16: Core modules

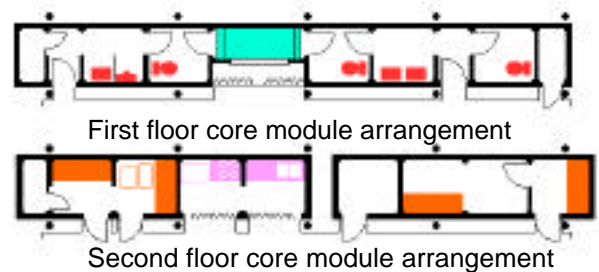


Figure 17: Core arrangements

Core modules are pre-manufactured special purpose rooms which are fully self-contained for the specified function. The modules are weatherproof and zip together and to the main structure with rubber gaskets. All plumbing, communications, computer equipment and such are located in the modules. The modules can be fully stocked with necessary equipment at the time of manufacture, shipped to the site, and plugged into place. Plumbing and power connections would have standard interfaces to ease mounting and demounting. Standard simple modules could be arranged to form more complex spaces such as restrooms, kitchens, and libraries.

The kit-of-parts system is joint-based, which means that a rigorous system of standard interfaces between parts is strictly observed, but the actual members themselves are "anything goes". This could facilitate the use of different materials or the creation of new parts that fit into the system. The joint system would be conceived in such a way that the possibility of incorporating power and communication infrastructures into the parts could be facilitated. This means that structural connection would also automatically complete wiring of the building since the "wiring harnesses" would be integrated into each part.

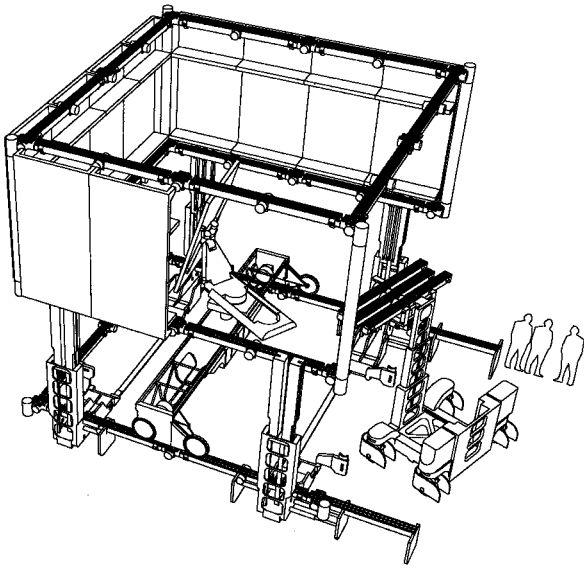


Figure 18: Robotic building system

AUTOMATED BUILDING SYSTEM DESIGN: In parallel with the component systems, the robots and automated construction machines would be designed also.

The shape grammars specify maximum and minimum bay widths but not bay depth. For this reason a robotic system is required which can expand or contract the width of its work cell according to the bay width, but extend its depth an unspecified distance. In the context of the example, a system of three robots was designed. One robot was a mobile autonomous forklift for carrying component pallets and materials. Another robot was a bridge crane-like robot with a special six-jointed robot attached for component installation. The third robot was a set of four

hydraulic jacks for lifting the already constructed portion of the building.

The three robots fold together into each other and are carried in the storage position by the forklift robot. In the construction sequence, the forklift would deploy the other two robots over a proposed bay location. The bridge crane robot would be waiting on a launch platform, the jacks would be ready to support the first-assembled structure, and the forklift would retrieve the first parts pallet. Next the bridge crane would begin taking girders from the forklift stack and laying them in a direction parallel with the bay depth. It would use the girders as rails to move up and down the depth of the bay, forklift following. In this manner an unspecified depth of a bay may be assembled, with the entire bay width fully accessible by the bridge crane robot. When a floor is complete, the bridge crane would move out of the way onto the launch platform and the jacks would lift the floor overhead and allow the assembly of the next floor. This sequence would continue until the proper number of floors for the bay was constructed, whereupon the set of three robots would pack up and move over to the next proposed bay.

This example automated building system has been tested and simulated on a computer: using CATIA robotics system.

Part III Summary

The research programme design proposed in part II was executed as planned. An automated construction simulation was executed and design principles derived. A partial shape grammar was derived, and finally, an example design implementation was presented. The research appears to have contributed valuable information.

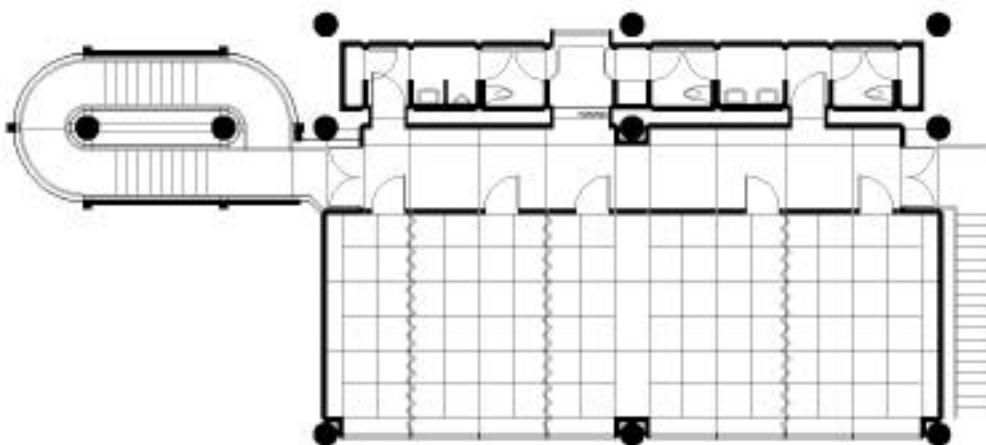


Figure 19: Second floor plan

Conclusion

In this paper the state of the art of automated construction was defined and some of the research of many of its key players delineated. It was determined that research initiated from the top-down, designer's point of view is lacking. In answer to the apparent gap, a research programme designed to cover some of the issues

concerning design for automated construction technology was proposed. Finally, the research programme was executed for the purpose of defining design principles that would be applicable to both the design of buildings and the systems that would construct them automatically. In addition to a shape grammar, six design principles were derived: 1) strong axis principle, 2) seventh joint principle, 3) assembly sequence principle, 4) interface principle, 5) stackability principle, and 6) path principle.

It is hoped that in the future more designers and researchers will take interest in automated construction principles. As a conceptual designer, the author looks forward to designing kit-of-parts libraries and spatial systems that will be assembled with robots and construction machines.

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- ¹² SCARA = Selective Compliance Assembly Robot Arm. Revolute joint axis of a SCARA robot are mostly oriented vertically such that the structure of the robot itself works to negate the force of gravity.
- ¹³ "Teach" mode: where each specific movement of the robot is initiated by a human operator in real time for the purpose of positioning the end effector at a desired location and orientation.
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