Designing for Automated Construction

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Abstract

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 first part of this paper is devoted to the design of a research programme which seeks to address topics related to the conceptual design of robotic systems for construction, and developing overall design principles for top-down architect / designer applications. The proposed research includes the derivation of simple shape grammars and a simulation research programme for understanding component connections and robotic manipulation, using a model robotic construction system remote controlled over the Internet.

The second part presents a report of the research carried out according to the programme, and introduces an example concept automated construction system designed according to the principles derived from the investigation outlined in the first part.

1:Introduction

Considering automated construction the questions can 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 preparation for this paper, the state of the art of automated construction was explored. Exemplars of papers and actual projects were identified and studied. Many of the questions asked regarding justification and feasibility have been discussed in the exemplars, but topics relating to design appear to be lacking.

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.

2:Research programme for design topics in automated construction

2.1:Background

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 tool 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.

2.2:Proposed 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 excercise 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.

2.3:Proposed 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 affectors 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

SCARA [2] 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.

2.4: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.

3:Research and design implementation

3.1:Background

In the previous section 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.

3.2: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" mode [3], 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.

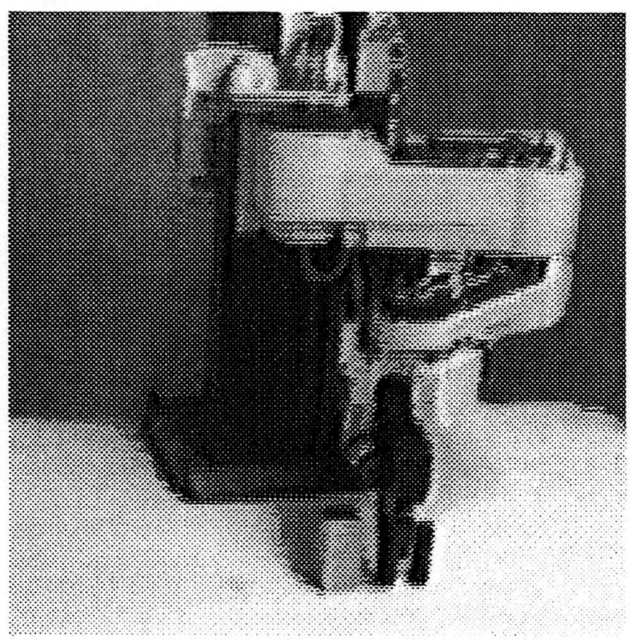

Figure 1: RTX robot

3.2.1: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 clasping 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.

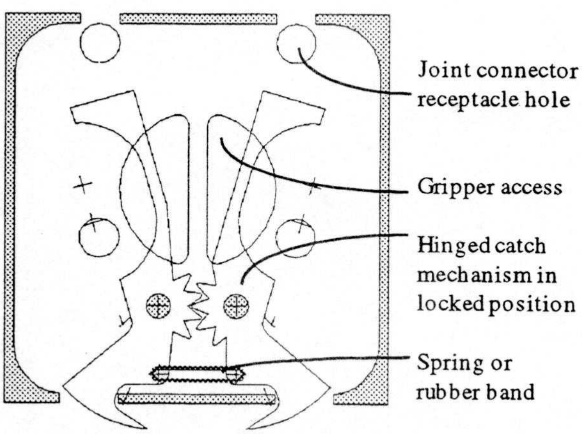

Figure 2: Wall component diagram

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.

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.

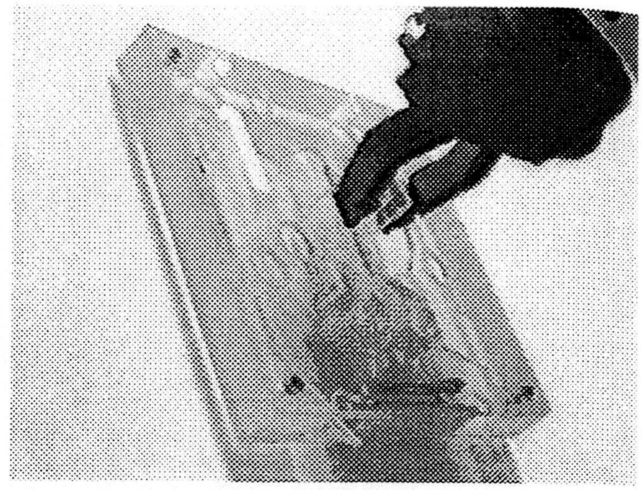

Figure 3: Disengagement of mechanism

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 affector 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.

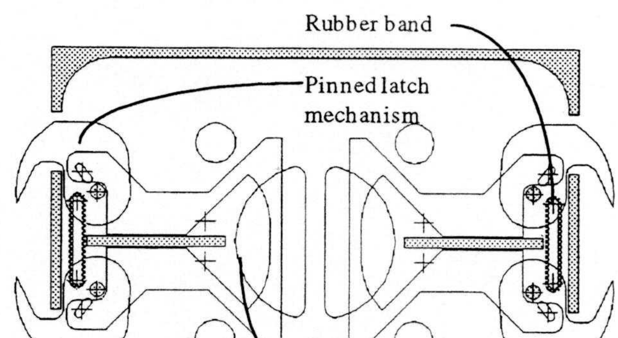

Figure 4: Floor component diagram

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.

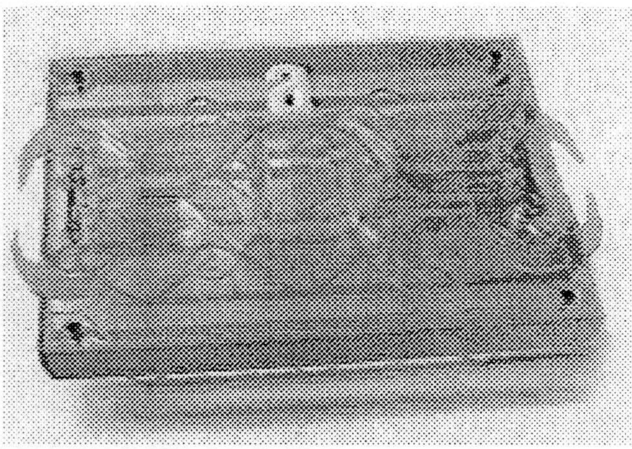

Figure 5: Model floor component

3.2.2: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.

Although the simulation was a success, there were several problems encountered during the excercise 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.

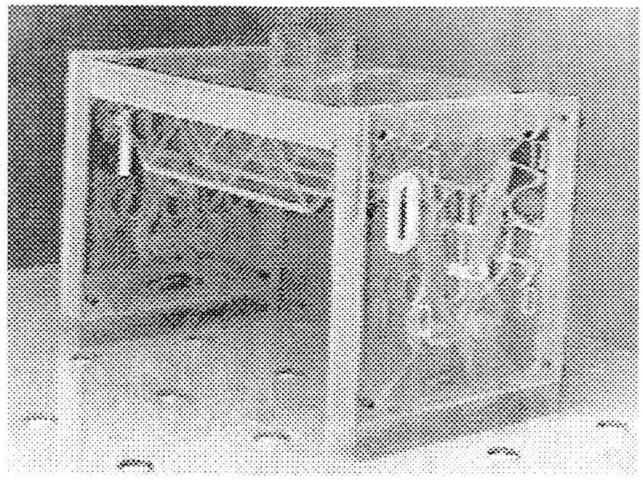

Figure 6: Constructed model

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.

3.2.3: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 affector. 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 affector 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 manufacturablity. 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 affector. How the above six design principles up-scale into the design of an actual building and robotic construction system would be a critical issue. The rest of this section will be devoted to solving some of these problems.

3.3:Theoretical shape grammar

The research programme in section 2.0 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.

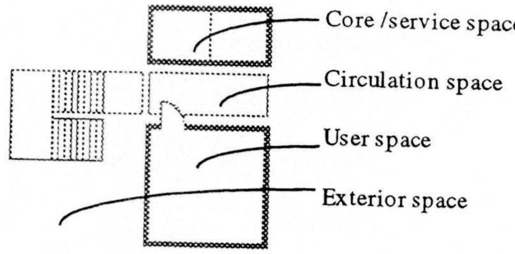

Figure 7: Space types

3.3.1:Shape 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 7, 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 7 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.

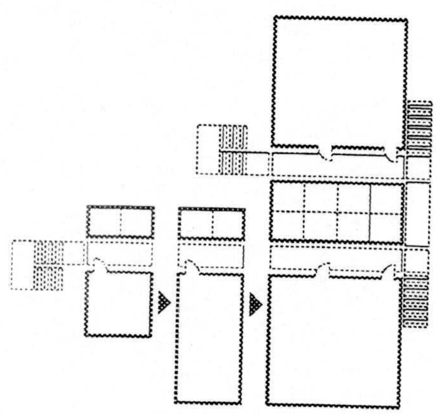

Figure 8: Additive bays

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.

3.3.2: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.

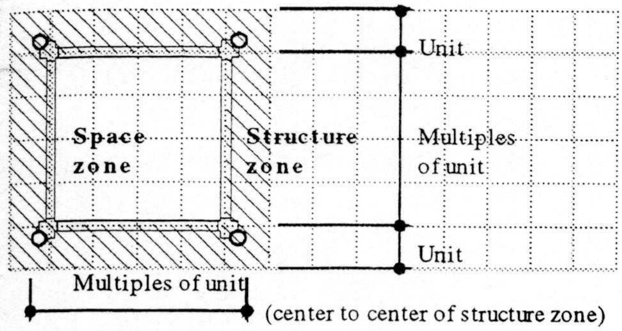

Figure 9: Space & structure zones

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 9 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 10 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.

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.

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.

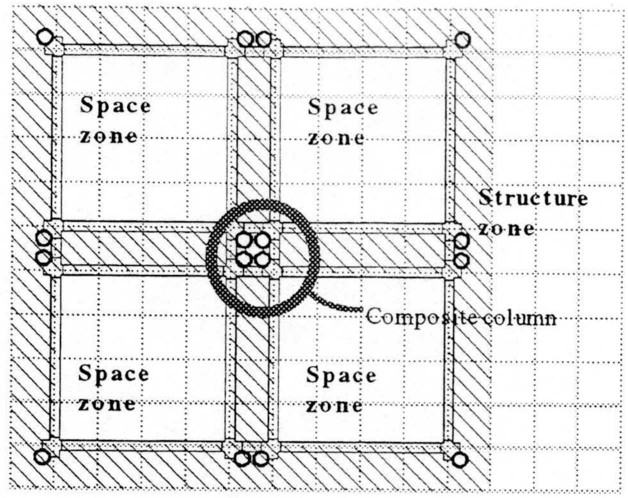

Figure 10: Adjacent bays

Figure 11 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.

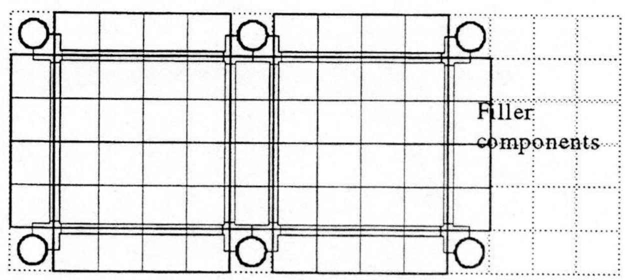

Figure 11:Continuous spaces

3.4:Design implementation

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

3.4.1: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 $300m^2$+ 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.

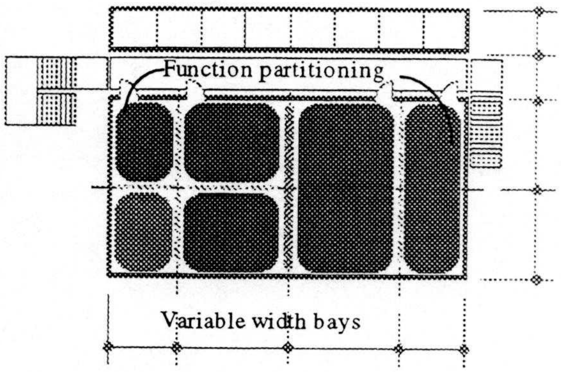

Figure 12: Space design

3.4.2:Space design. It is decided that the plan will basically be linear with several bays side-by-side according the 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.

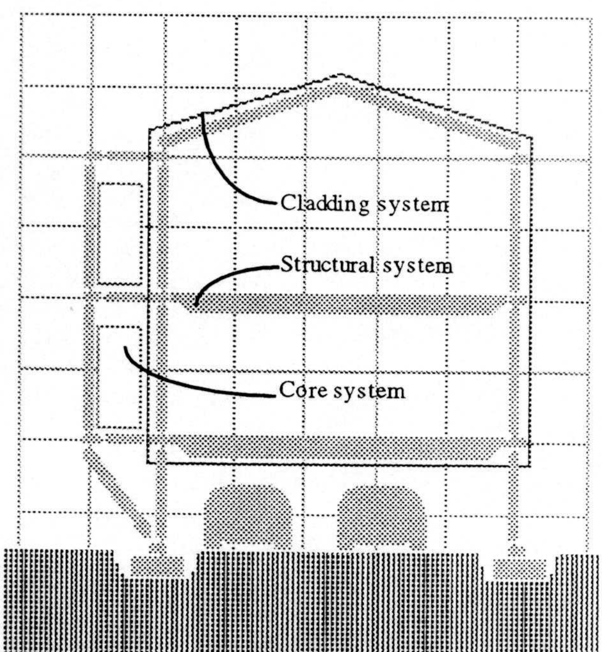

Figure 13: Component building systems

3.4.3: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.

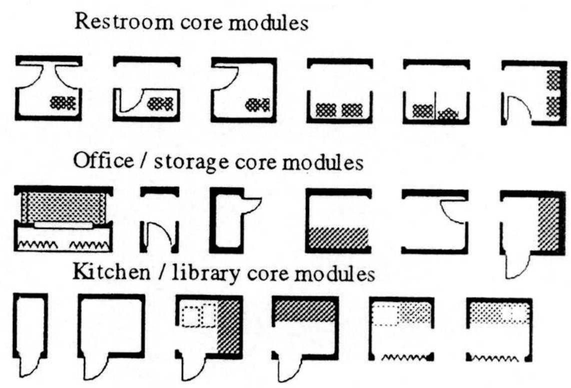

Figure 14: Core modules

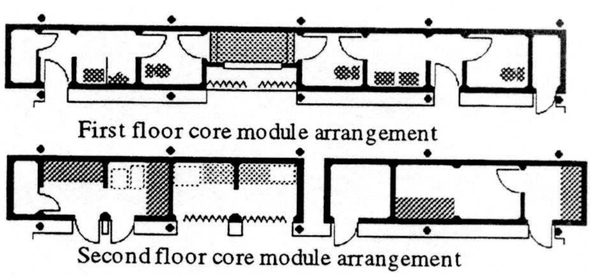

Figure 15: Core arrangements

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 de-mounting. 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 can be anything the designer feels appropriate. 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.

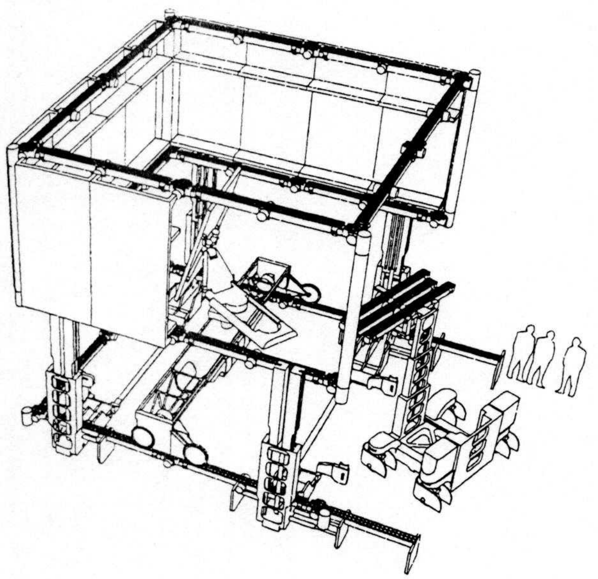

Figure 16: Robotic building system

3.4.4: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.

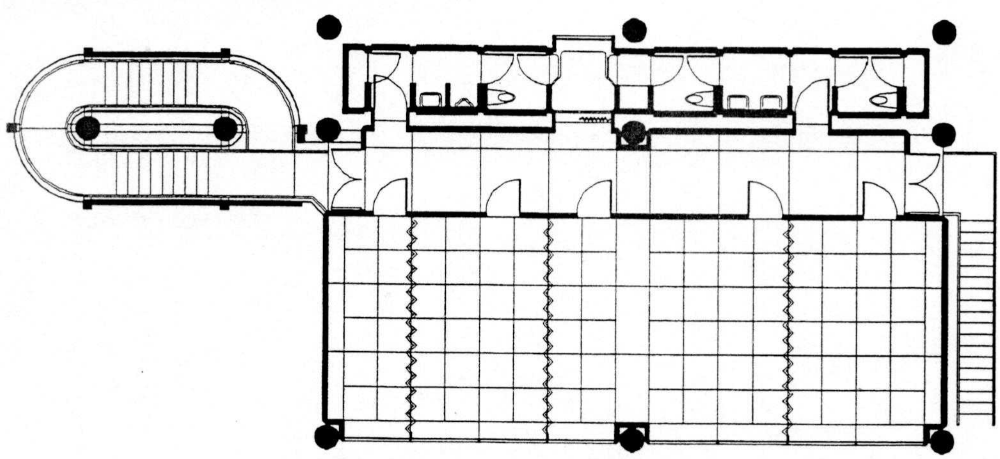

Figure 17: Second floor plan

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

3.5:Summary

The research programme design proposed in section 2.0 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 which is based on the derived principles and shape grammar.

4:Conclusion

In preparation for 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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