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. In order to optimize the use of automated technology, it is important that design principles based on the technology are considered. This paper seeks to address topics related to designing robotic systems for construction, and developing overall design principles for top-down architect / designer applications. The research herein is divided into a theoretical research programme for the purpose of deriving a simple shape grammar and a simulation research programme for understanding component connections and robotic manipulation. The second part of this paper introduces a concept automated construction system designed according to the principles derived from the investigation.

1. Design Topics in Automated Construction

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.

1.1. AUTOMATED CONSTRUCTION SIMULATION

In order to come to a partial understanding of the implications of using robots for building construction, a simulation using a real robot to construct a model building was conducted. The simulation provided a testbed for component connection concepts, component / manipulator relationships, and robot control.

1.1.1. Robot Work Cell and Model Components

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. When
the overall functions of the robot and the limits of its work cell were understood, the simple model component building system was tentatively designed. The components kit-of-parts were designed around a 10cm three-dimensional grid with simple locking connectors.

![Diagram of model wall component with labels: joint connector receptacle hole, gripper access, hinged catch mechanism in locked position, spring or rubber band.]

*Figure 1.* Model Wall Component.

![Image of mechanism in disengagement process.]

*Figure 2.* Disengagement of mechanism.

The joint mechanisms were devised to be continually spring-loaded, engaged in the locked position, and only when pressure is applied by the robot’s end effector can the mechanism disengage for installation or disassembly. Installation of the panels would be facilitated by lifting the panel into position at receptacle holes and releasing the hinged catches to allow them to
engage in the holes.

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 represented the building site, with potential joint receptacles ready to receive components in any location or orthogonal orientation on the grid.

1.1.2. Construction Simulation
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.

Altogether 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 over the Internet from Japan and Denmark.

1.1.3. 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 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 was 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 was 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 hidden behind other parts should be placed first while there is still access. Decidedly a construction problem, well thought-out designs could nevertheless contribute to constructability in this area. This principle was 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 grasp points can be designed into the aesthetic of the building. This principle was 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. 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. These paths are mainly a construction problem, but careful thought during the design stage could improve manufacturability. This principle was coined as the “path principle”.

1.2. THEORETICAL SHAPE GRAMMARS

In the research proposed in this paper an excercise deriving constructive theoretical shape grammars for an orthogonal building was conducted. The purpose for deriving a grammar is to provide a set of guidelines for allowed or disallowed space adjacencies, and to generate rules for individual component shape. Structural requirements for the pre-engineering of individual components and hints about their potential interface with robotic construction systems can also be derived. Space generating grammars conforming to robotic work cells, or work cells conforming to space generation all have an effect on the overall building design.

1.2.1. Space Generation Grammars
Four basic types of spaces were addressed: user space, circulation space, core/service space, and exterior space. Circulation spaces function as a trunk with core/service and user spaces opening off of it as required.

![Space types](image)

*Figure 4. Space types.*

The space arrangement in figure 4 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.

1.2.2. *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.

![Space and structure zones](image)

*Figure 5. Space and structure zones.*

Figure 5 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 6 the structures of two bays are shown completely independent of each other. 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.

![Diagram](image)

*Figure 6. Adjacent bays.*

![Diagram](image)

*Figure 7. Continuous spaces.*

Figure 7 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.
2. Design Implementation

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

2.1. BUILDING DESIGN

An example design problem for a 300m²+ church, school or business teaching / training facility was used to apply the principles. 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.

![Diagram of building design](image)

*Figure 8. Space design.*

2.1.1. Space Design

It was 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.

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.

2.1.2. 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 which are self-contained with plumbing and wiring harnesses.
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.
2.2. AUTOMATED BUILDING SYSTEM DESIGN

In parallel with the component systems, the robots and automated construction machines were also designed according to the shape grammar.

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.

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

3. Conclusion

In this work the state of the art of automated construction was studied and some of the research of many of its key players noted. 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. 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 simple 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 an interest in automated construction design principles.

References


