DIGIOSK

Digital Design to Robotic Deployment in Two Months

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Abstract. In this paper, we discuss Kit-of-parts Theory and how it applies to the design, manufacture, and operation of a small robotic deployable demonstration structure called the Digiosk (Howe, 2001). "Kit-of-parts Theory" refers to the study and application of object-oriented building techniques, where building components are pre-designed / pre-engineered / pre-fabricated for inclusion in joint-based (linear element), panel-based (planar element), module-based (solid element), and deployable (time element) construction systems. The Digiosk is an exposition display kiosk that was designed and manufactured digitally, and brought from concept to robotic functionality in a short period of time. Using kinematic mechanisms the cylinder opens up and deploys into a 2.7m cubical display booth complete with integral power and network connections. The kiosk was designed using a solid modeler, from which data was extracted to drive digital manufacturing processes. Owing to the well-developed understanding of Kit-of-parts Theory and the new "kinematic architecture" principles, the paperless process yielded a working prototype only eight weeks after initial conceptualization. The paper concludes with a discussion of how these concepts can be applied to large-scale projects and design processes.

1. Introduction

The kit-of-parts approach is a way to formalize the essence of an artifact in a quantified, repeatable, systematic way. Using design grammars, a few cleverly designed primitives can be combined in countless ways to produce many different types of useful objects and structures. We can also impose another formal order on the artifact's life-cycle timeline as well, breaking up the myriad of minute influences acting upon it into their composite primitives of translation, rotation, and spatial placement. This set of primitive events can be a parallel kit-of-parts consisting of time and motion forming the essence of the artifact's existence and function. Combining these two sets and formalizing the way they react with one another can provide a powerful language of artifact creation that encompasses not only geometry and function, but also life cycle processes for existence and behavior. Matching "geometry primitive" kit-of-parts with "motion primitives" define a form of "kinematic architecture" that includes mechanisms to construct itself (Bridgewater, 1993), or to change the configuration or form of the structure over its lifetime.

To the advanced degree that we have considered this relationship as the basis for a robust kit-of-parts system design, the digital representation of the system becomes almost as important as the nature of the physical components themselves. Through the use of a digital model, kit-of-parts systems can be monitored or controlled remotely in real time, and can be instrumental in the entire lifecycle of the artifact, from conceptual design through manufacture, assembly, use, and eventual dismantle. The digital representation of the system is so critical that we have considered physical products as mere analog instances of the well-structured original digital model, generated directly from the model and repeated as many times as necessary. We have made the following assumption:

> "The digital building model should output a real-world counterpart of itself, much the same way a word processing document becomes hard copy in a printer."

In the course of our research we have tested and simulated various concepts relating to this assumption, such as geometry and formal categories of systems (Howe, Ishii & Yoshida, 1999), virtual management and control (Howe, 1997), working models, digital manufacturing, and robotic assembly (Howe, 1998), and motion primitives (Howe, 2000). What was needed was a small scale structure that included requirements for kinematic function, that could be designed from scratch according to all the ideas considered so far. The Digiosk project provided the opportunity to generate a fully working prototype from an initial digital model at a manageable scale.

1.1 KIT-OF-PARTS THEORY

"Kit-of-parts Theory" refers to the study and application of object-oriented building techniques, where building components are pre-designed / pre-engineered / pre-fabricated for inclusion in joint-based (linear element), panel-based (planar element), module-based (solid element), and deployable (time element) construction systems. Kit-of-parts construction is a special subset of pre-fabrication that not only attempts to achieve flexibility in assembly and efficiency in manufacture, but also by definition requires a capacity for demountability, disassembly, and reuse.

1.1.1 Geometry primitives

"Kit-of-parts design" involves organizing the millions of individual parts and raw material in an artifact into assemblies of standard easy-to-manufacture components, sized for convenient handling or according to shipping constraints (Diamant, 1965). The construction of the artifact is carried out on the assembly level as opposed to the raw material level. The architect defines a parts library describing every major assembly in the building (Davies, 1988). The assemblies are conceived in a systematic way, based on certain rules such as increment, size, or by shape grammar (Mitchell, 1990). Standard connections between the assemblies are carefully defined, so the number of possible shapes and appearance the parts can take is limitless. Kit-of-parts and prefabricated systems fall into four main category types: joint-based, panel-based, module-based, and deployable, which includes pneumatic inflatable structures. Combinations of the various categories are also present in hybrid structures.

Joint-based (Linear Element): Examples which fall into the joint-based category have clear distinctions between the members and joints, and often celebrate the joint with some special design or connection technique that either enhances the ease of assembly or speeds erection time. These systems are characterized by functional linear structural elements (often optimized for size and sectional characteristics) that may fasten to a nodal joint element, reminiscent of point and line. Joint-based systems are appropriate for secondary support structures.

Panel-based (Planar Element): Panel-based systems essentially incorporate structure and wall / floor cladding and decks into one-piece assemblies. An assembly consisting of raw materials becomes a discrete component that works as a single structure or cladding member. Upper-end panel-based systems often have specially designed fasteners along their edges that connect to each other and ease the construction process. In panel-based systems, the design of the seam occurring between two panels is critical to insure a successful weatherproof enclosure. Since the panels act as both structure and cladding elements at the same time, gaskets or built-in devices for weatherproofing must be used.

Module-based (Solid Element): Modules are entire volumetrics or blocks that are assembled in advance and set into place at the site. Because of the size and scope of each component, the number of necessary modules required in a construction is usually much less than panel or joint-based systems. Module-based construction can represent an entire self-contained building with a single unit.

Deployable (Time Element): Deployable structures consist of folding trusses, swing-open modules, and inflatable structures. Various truss designs, including domes, space trusses and folding vaults for the purposes of maintaining a compact and / or lightweight profile have been developed for instant site deployment. The division of service space and user space at various scales, from workstation to entire buildings, map into various densities of hard structure / installation versus void. Core elements are denser, where corridors and spaces are less dense. The superior advantage of deployable-based systems is that the less dense areas are designed to collapse at appropriate points during their use in order to greatly reduce volume or double and triple functions occurring in the same space.

Hybrid Systems: Often elements from several categories are used together in the same structure. Kit-of-parts systems can be designed with various types of elements, such as combining linear element for structure and planar element for cladding.

1.1.2 Motion primitives

Architecture is becoming more and more kinematic in nature, especially when we consider facades and roof systems that actively respond to their environments. In the same way that architects must understand basic principles of statics in order to conceptually design structures that will successfully stand up, it is also becoming necessary to have a basic knowledge of kinematic principles to understand the sometimes complex behavior of these moving parts. A kinematic mechanism can be defined as a structure containing two or more elements that have the capacity to alter their configuration in relationship to each other based on a known or given transformation. The transformations consist of either translation or rotation, singularly or in any given complex combination. The transformations are defined and constrained by the geometry of the elements in the structure. A robotic mechanism is a structure containing one or more kinematic mechanisms, one or more actuators, one or more sensors, and a controller. The robotic mechanism functions as a device to perform a predefined work such as to reconfigure a kinematic mechanism according to outside instructions (Kurita, Tezuka & Takada, 1993). The robotic mechanism works as a feedback loop: the controller receives external instructions to perform a certain work and directs the actuator to perform it. Then the sensor continually senses the current state or configuration of the kinematic mechanism and notifies the controller. Finally the controller makes a continuous judgement as to what degree the work has been performed, and instructs the actuator to continue or correct itself. When the work has been completed, the actuator is stopped.

Complex systems consisting of multiple kinematic and robotic mechanisms require coordinated behavior and work areas, which are system-wide work cells. A robotic mechanism assigned to perform a certain work should be supported by other systems such as infrastructure / service elements, circulation, and structural systems that overlap in their hierarchy of support of a multitude of smaller work cells. In this way we've considered buildings to consist entirely of overlapping work cells of active and passive robotic mechanisms.

1.2 DIGITAL REPRESENTATION

For advanced virtual management, linking the digital element with the physical element is the key. This can be done by installing smart sensors and actuators into each kit-of-parts component, so that as the physical elements are connected, a virtual representation of them are connected as well. Using Direct Digital Control (DDC) technology (Newman, 1994) with standards such as LonWorks, a 'fieldbus' network can be established with unlimited configurability. The term 'fieldbus' refers to a series of nodes connected along a single line. One signal goes out to all the devices, but only the summoned device answers. Just as computers are given unique addresses, standards have been developed which give each smart device a unique address in the system. Nodes are linked with controllers, sensors, and actuators so that all nodes broadcast or publish their information to all other nodes, and messages are received only if they are programmed to do so. Establishing a web-based information management system (Fukai, 1997) can allow remote monitoring and control.

2. Approach

Kajima Corporation, our long time partner and collaborator in kit-of-parts and automated construction research, was in need of an exposition booth to showcase their automated construction technology. It was decided that the booth itself should embody some of the technology, including robotic capability. Our previous research prepared us to incorporate the technologies. However, the time schedule for completing the project was extremely tight, with only three months allowed for concept formulation, design, manufacture, assembly, and testing in the United States, and delivery to Japan. Under these stringent conditions the Digiosk was conceived.

2.1 THE DIGIOSK

The Digiosk is an exposition display kiosk that was designed and manufactured digitally, and brought from concept to robotic functionality in a short period of time (Figure 1).

Figure 1: Digiosk exposition booth

In its stowed form, the Digiosk consists of a 0.9m diameter cylinder 2.7m high. Using kinematic mechanisms the cylinder opens up and deploys into a 2.7m cubical display booth complete with integral power and network connections. The Digiosk was installed with a LonWorks direct digital control network and router to affect remote control of deployment over the Internet.

The combinations of sensors and actuators used for deployment and stowage of the kiosk were to constitute a robotic feedback loop (however, in the limited time allotted for its actual construction the deployment mechanism ended up being only partially robotic). The kiosk was designed using a solid modeler, from which data was extracted to drive digital manufacturing processes. Owing to the well-developed understanding of Kit-of-parts Theory and the new "kinematic architecture" principles, the paperless process yielded a working prototype only eight weeks after initial conceptualization.

2.2 RESEARCH TASK

Even with the tight schedule, the task remained to produce a valid embodiment of the kit-of-parts geometry / motion primitive combination concept, managed by its digital representation. Another aspect of our approach required us to conform as much as possible to our assumption, that a digital model should be able to output a real-world counterpart of itself. This required that only digital manufacturing processes could be used in the production of the prototype, forming a new kind of constraint in the design process. With these tasks in mind, the research took a combination of three clear approaches: interpretive, simulation, and action research strategies.

2.2.1 Interpretive Approach

The interpretive approach consisted of design investigations based on Kit-of-parts Theory. Using a variety of design grammars, several alternative design interpretations were explored for the purpose of understanding appropriate functional solutions for the problem context. Some of the knowledge produced in the interpretive investigation was used directly to generate a satisfactory model for further study. Other knowledge was cataloged away for future alternative applications in similar contexts.

2.2.2 Simulation Approach

Once likely solutions were chosen, simulations were conducted to test the function and deployment of the kiosk. The simulations included digital models used for kinematic analysis, physical models constructed on an analog process similar to that which would eventually be used for final digital manufacturing, and computer animations. The knowledge created during this process contributed toward the successful final manufacture and assembly of the working prototype in such a short period of time.

2.2.3 Action Approach

The action portion of the investigation consisted of the actual manufacture, assembly, and testing of the prototype, as well as the observation of its extended use under the original exposition context and other subsequent contexts. Knowledge created during this process contributes toward a validity of scaled-up approaches used in the digital construction of entire buildings, as will be discussed later.

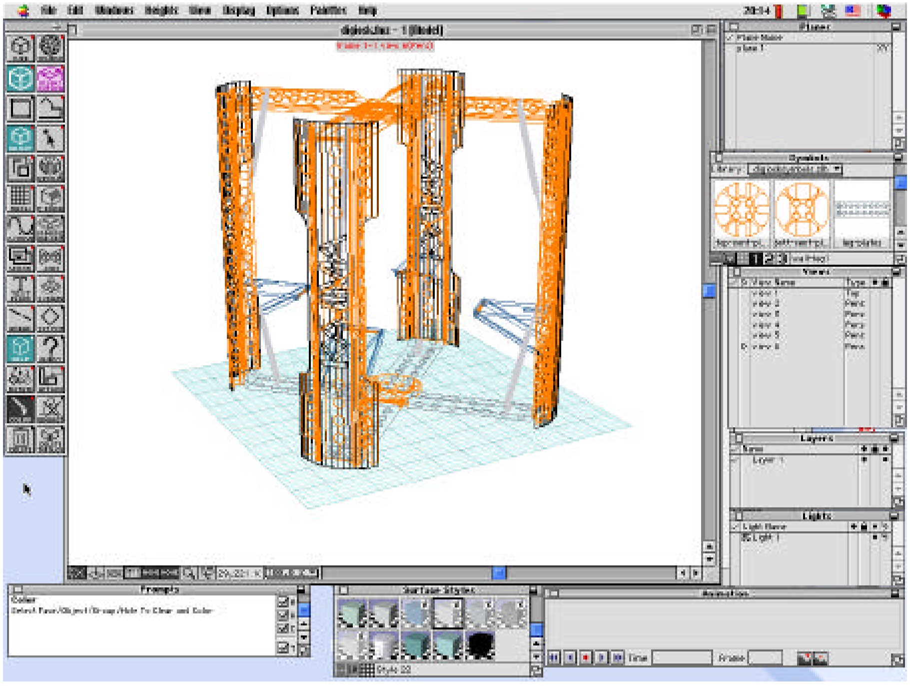

Figure 2: 3D modeling on Form-Z (used for both conceptual volumetric "sketching" and resolution of the final design)

3. Process

In our short time schedule, it would have been impossible to solve all the problems of data representation that would support a single rich model capable of outputting multiple formats required for design, digital manufacturing, robotic operation, management. However we did limit ourselves to a single source model, that was created during the design process, to produce all of the various data files. Using a single digital model, the component processes were design process, modeling process, and construction process, corresponding to the interpretive, simulation, and action research approaches.

3.1 DESIGN PROCESS

The design process involved two teams, one located in Sendai, Japan (the client), and the other located in Eugene, Oregon (the design team). We worked almost entirely online, exchanging models and rendered images via email among ourselves and in communication with the client. In both locations it was possible to meet face to face for discussions within the teams, but distances dictated the necessity to use electronic communication between teams.

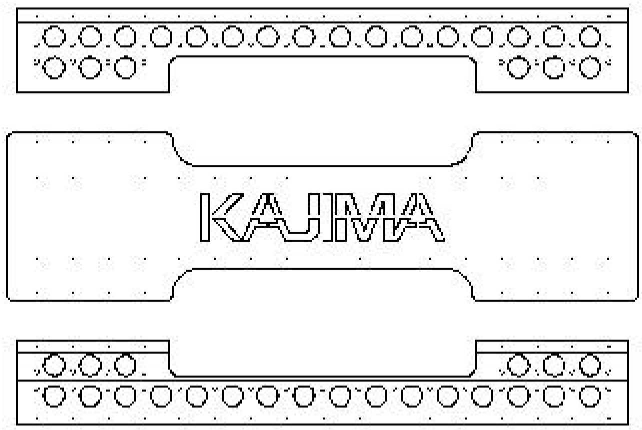

Figure 3: Using Form-Z to unfold the model into fabrications

Since the kiosk needed to be portable, we considered several joint-based, panel-based, and module-based systems and hybrids before deciding on a deployable concept. The various design exercises were conducted in accordance to what we knew about robust kit-of-parts system design and how similar systems have failed in the past. This included the consideration of not only flexible, reconfigurable components, but also hierarchical geometry relationships, hierarchical motion relationships, nesting, and self-generating hierarchical infrastructure. We were given specifications for size allotments and also knew about the context of the display area (locations of other booths, the nature of the exhibition building, etc), and also understood that the kiosk could be used in entirely different contexts in the future. A robust kit-of-parts system may have a pure core organizing principle, allow for expansion, and include mitigating elements that allow it to interface with the context (the context may have its own organizational principles that need to be addressed). Owing to these complexities, a self-contained deployable unit with a simple plan accessible from all sides was chosen, especially since the kinematic nature of the deployable structure would meet the objective of demonstrating automated construction principles.

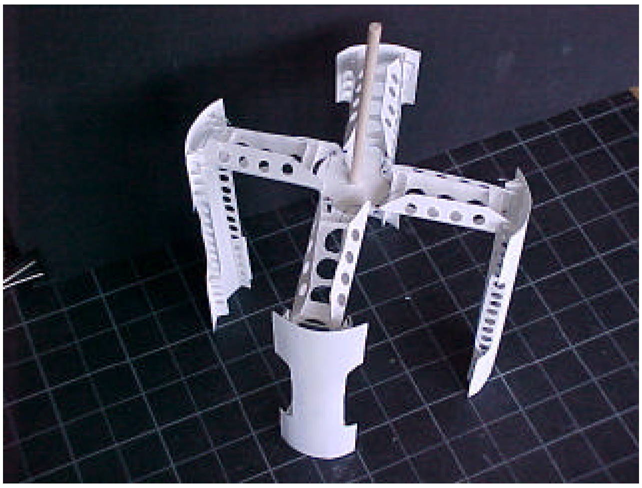

Figure 4: Paper model approximating sheet metal construction

During the design phase, we used both Macintosh and PC computers running Form-Z 3D modeling application (Figure 2). The team members were well-versed with paperless sketching techniques, employing quick primitive generation with transformations, Boolean operations, and symbol / instance population. Though some paper sketching was done, the majority of the sketching used these digital techniques, often with several team members gathered around a single computer. Form-Z has no real kinematic analysis capability. However, we were able to do limited explorations using the Form-Z transformation tools, testing revolute or prismatic motion on non-nested individual kinematic mechanisms.

The design process produced a baseline 3D model that we exported to various other software applications for additional analysis and further processing.

3.2 MODELING PROCESS

Using the Form-Z model, 2D flattened drawings were extracted for the purpose of producing templates to cut sheet materials in physical models, and to drive the digital laser cutters at the factory (Figure 3). Numerous physical models were produced from the templates, which helped us to understand how the kiosk folded and deployed itself, and how the various pieces fit together. This included paper models of various scales (Figure 4), and rough sheet metal approximations cut from any scrap metal materials we could find. Since we did not have a laser cutter available during the modeling stage, all templates were printed out onto paper and either cut by hand or traced over onto other materials.

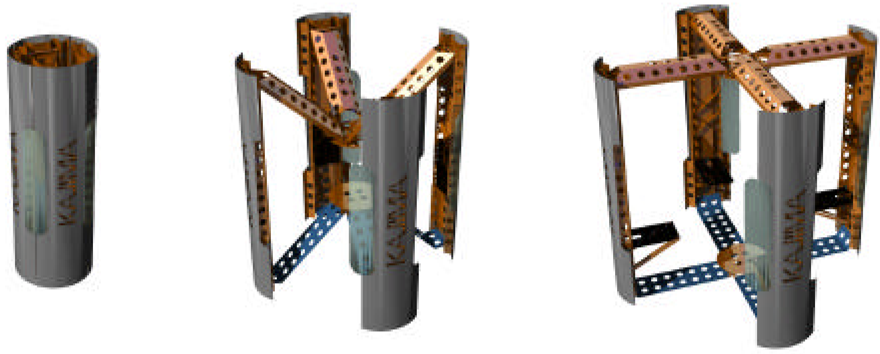

Figure 5: Computer simulation of deployment sequence

The Form-Z model was also exported into an animation software that allowed us to simulate full nested kinematic functionality. The computer animation could show the kiosk open and close from any desired angle and help to resolve conflicts (Figure 5).

3.3 CONSTRUCTION PROCESS

Once we were satisfied that the digital components all fit together and worked, the 2D flattened drawings were exported into AutoCAD, separated into layers representing cutting lines, folding lines, and descriptive information, and sent via email to the manufacturer. A noteworthy part of the design included a hierarchical approach to fastener design. Three tiers of fastener types were devised, relating to size, load, and permanence. The fasteners were planned on a grid whether they were needed or not, to allow for future flexibility. As the fabrications began arriving, they were carefully tested and fit together (Figure 6). We were pleasantly surprised that all fabrications fit together in almost perfect precision the first time (very few slight variations were due to bending, and were within acceptable tolerances).

Testing and design of pneumatic actuators and power system occurred in parallel with the assembly. A series of manifolds, solenoid valves, and plastic tubing were connected to the actuators and tested before insertion into the kiosk structure. The final design consisted of four “quarter panel” sub-assemblies attached to a central radial node assembly.

Figure 6: Fabrication assembly

The final (though unpainted), fully assembled robotic kiosk was tested almost exactly eight weeks after the first Form-Z primitive was input into the computer (Figure 7).

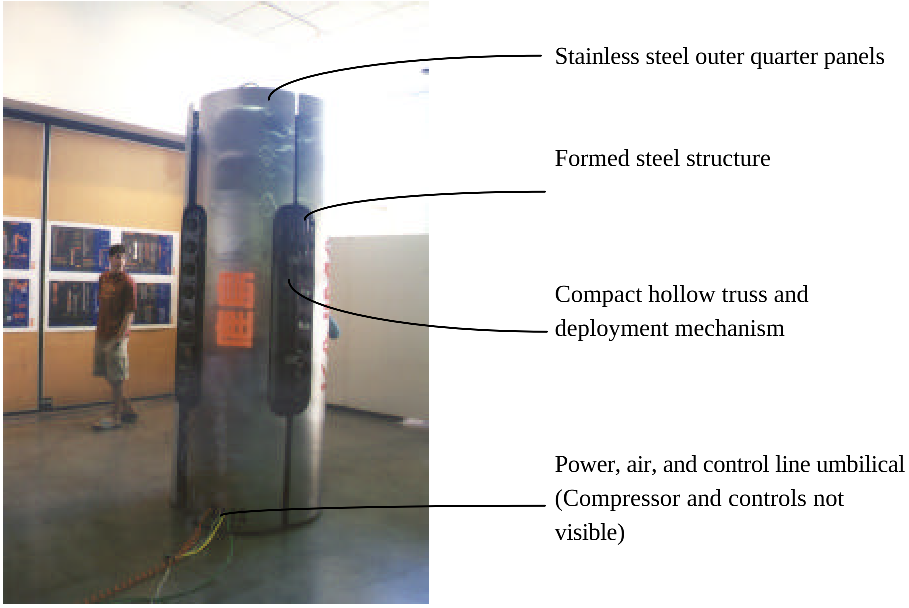

Figure 7: Digiosk in stowed position

Several public demonstrations of repeated pneumatic deployment and stowage were conducted in front of University of Oregon students and faculty before the structure was dismantled and sent out to be painted. Two weeks later, the components came back in brilliant colors and we reassembled the quarter panels, loaded them into wooden crates, and shipped them off to Japan. A month after that, both client and design teams gathered in a small warehouse in Sendai, Japan to do the final assembly and deployment test.

Figure 8: Manual preliminary setup required

4. Findings

The Digiosk experiment went a long way to support the Kit-of-parts Theory research components of geometry / motion primitive concepts supported by a digital model. Following design grammars optimized for hierarchical structure generation gave satisfactory design results, and digital manufacturing techniques working from the same digital model allowed the project to be completed in a minimal amount of time. Several aspects were supported, of the assumption that digital models should be originals driving the production of physical instances of themselves.

However, the exercise left many gaps to be completed on future explorations. The most noteworthy gap is the lack of a single rich data representation from which all processes are driven. Though everything was derived digitally, a lot of manual manipulation and optimization was required to bring each file up to a useable level. Another gap was the lack of automation in the manufacturing / assembly process. Though laser cutters could be driven by data files derived from the main model, other tasks such as bending, painting, material handling, and assembly all had to be performed manually. The original intention of creating a compact, deployable structure was to provide a portable unit that could easily be relocated and set itself up. However, since it doesn't fit through typical doors and is quite heavy, the structure must be broken down into quarter panels (Figure 8) and manually handled separately.

Another problem that wasn't solved at the time of delivery was the full robotic functionality (a full feedback loop was not implemented), and remote web control, though these have been tested in separate applications (Howe, 2001).

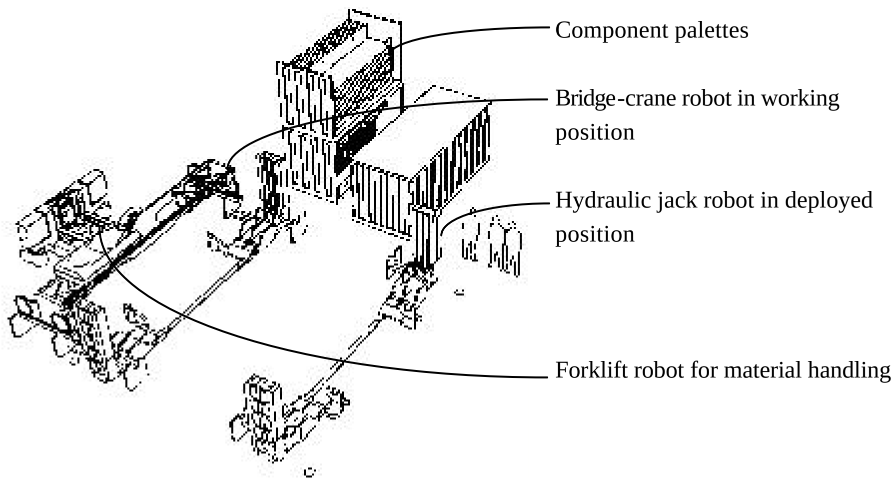

Figure 9: LDS Building system

5. Conclusion: scaling up

We have been involved with several projects that apply kit-of-parts and automation concepts to large-scale structures. The LDS Building System (Figure 9) employs three robots that create a full construction system of overlapping work cells that serve each other, including material handling and positional displacement (Howe, 2000). Kajima's AMURAD system jacks up the completed structure, and builds the floor underneath. AMURAD has constructed two mid-rise buildings. The Plug-in Condominium project uses automation to manufacture container-shaped modules in a field factory, and inserts them into a centrally maintained infrastructure support structure. The modules can be removed and relocated to other similar structures, all the time maintaining hierarchy in infrastructure.

However, these projects do not apply kit-of-parts concepts in an elegant way, formalizing relationships between geometry and motion primitives, or employing a single digital model to extract all manufactured components. The Digiosk project has become a vehicle for this experimentation, which will be applied to these large-scale projects.

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