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Design Principles for Kinematic Architecture

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Abstract

The kit-of-parts approach is a way to formalize the essence of an artifact in a quantified, repeatable, systematic way (Howe, Ishii & Yoshida, 1999). Using design grammars, a few cleverly designed primitives can be combined in countless ways to produce many different types of useful objects and structures (Howe, 1998). 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 (Howe, 2000). 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, or to change the configuration or form of the structure over its lifetime.

In this paper, nine design principles are described that define a truly kinematic building architecture (Howe, 2002).

Keywords

Kit-of-parts, automated construction, kinematics, grammar

1. Introduction

Through the application of expandable design grammars, shape grammars, and open-ended procedural rules, flexible parametric kit-of-parts systems can be defined that are adaptable to any contextual setting. A few cleverly designed primitives can be combined in countless ways to produce many different types of useful objects and structures. In effect, after analyzing and identifying common configurations in geometry and function, the kit-of-parts approach is a way to formalize the essence of various artifacts in a quantified, repeatable, systematic way. Since a well-designed component can be mass-produced and used over and over again, fabrication processes can be worked out in advance for robotic manufacturing and automated assembly. If we consider these processes as significant steps in an artifact's life cycle, perhaps we can impose another order on the 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. 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.

2. 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.

Kit-of-parts architecture involves organizing the millions of individual parts and raw material in a building into assemblies of standard easy-to-manufacture components, sized for convenient handling or according to shipping constraints. The construction of the building 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. The assemblies are conceived in a systematic way, based on certain rules such as increment, size, or by shape grammar. 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 philosophy goes hand in hand with advanced manufacturing, automation, and computer and information technologies. Handling multiple identical components as instances of a master element is an efficient use of the computer in the planning stage, and use of standard components can take advantage of mass-production technologies.

2.1 Kit-of-parts Categories

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.

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.

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 ingenious 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 in their lifetime 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.

2.2 Higher Organization

In higher level organizational concepts, the kit-of-parts elements are already defined with rules of interface with each other, so that they can define any number of volumes and spaces in a flexible way. Therefore the rules govern not the components, but the connections between them. Primitives in the system have their own set of simple rules. When the primitives are nested into more complex organizations, the new entities formed have a new set of rules. These new entities can then be combined with each other to form even larger entities governed by their own rules, and so on.

Basic ordering principles for spaces include linear, centralized, radial, cluster, nodal, and grid modified by axis, symmetry, hierarchy, rhythm, datum, and transformation (Ching, 1996). The basic ordering principles can apply at any scale, including individual part design or bolt layout, all the way to planning for entire cities. In kit-of-parts system definition, it is understood that the same elements may be used for a variety of situations.

2.3 Design Grammars

Buildings and other artificially created structures have three-dimensional mass and volume, and consist of sophisticated combinations of different shapes. If it were possible to extract the shapes in such a way as to define a finite number of basic primitives, a shape "alphabet" of sorts could be derived which could potentially be used to describe the structure. If rules governing the various combinations of the shape primitives could be established, an underlying shape language which describes not only the original building, but other similar (and possibly non-similar) structures could be derived. In this way, each building and construction system has its own language and grammar, whether formal or implied in the design process.

Human habitable structures consist of multiple systems organized in hypothetical tree structures, where the leaves do all the detail work and transfer their loads to larger and larger branches to the trunk until it is resolved at the ground. These systems include structure, circulation, spatial hierarchy, and other systems. Grammars can be useful to define rules for how the trees branch off and do their job, and also how the separate functions are integrated.

Design grammars not only provide a way to design joint-based, panel-based, module-based, and deployable kit-of-parts building systems according to higher level ordering principles, but they can also be used to guide the design of the machines and equipment used to assemble the parts during the construction process. This is especially true if the machines and equipment are also constructed out of the same kit-of-parts system. The next section will discuss automated and robotic construction, and how it can harmoniously fit in with Kit-of-parts Theory.

3. Automated Construction

Automated construction technologies have arisen out of the need to introduce greater efficiency into construction processes, incorporate information-based technologies, eliminate dangerous site conditions and address labor shortages. Though the industry has called for incremental development, the goal of the researcher has been to produce a fully autonomous design / construction system which can be controlled or monitored remotely throughout the entire life cycle of the building.

To realize the dream of full autonomy, recent construction automation research not only attempts to establish feasibility and develop more robust marketable systems, but also strives to organize the digital representation of process, product, and machine. The eventual scenario dictates that the digital building model will know how to output its own real-world counterpart through information infrastructures and automated manufacturing systems much the same way a word processing document becomes hard copy in a printer. Automated construction systems that have been fully implemented fall into three major categories:

- Collections of function-specific robots that work independently of each other
- Robotic systems which form a systematic "factory" that is stationary or fixed in the context of the site
- Robotic systems which form a systematic "factory" that moves itself along as it completes portions of the building

Our research has included systems in all three categories, and has included topics in material handling, site work, power & communication, reconfigurability, field factory, and multi-directional assembly (Figure 1).

Partially completed building lifted into place
Robotic support structure
Six-ton capacity lift jacks
Stacked component containers
Bridge-crane robot in waiting position
Forklift robot
Dedicated hydraulic-jack robot
Foundation socket point

Figure 1: Automated construction: AMURAD (left), LDS Building System (right)

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.

Kinematic Mechanisms: 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.

Robotic Mechanisms: 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. 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.

System-wide Work cells: Complex systems consisting of multiple kinematic and robotic mechanisms require coordinated behavior and work areas. A robotic mechanism assigned to perform a certain work should be supported by other systems such as material handling systems. Construction sequences should be planned to allow the various robotic mechanisms to work freely and have access to the site. System-wide work cells would include advanced construction techniques such as the Field Factory approach or multi-directional assembly concepts that have advanced material handling capability.

If architects understood these basic principles they can participate in optimizing the design of both the mechanisms and building modules manipulated by them. Indeed, such a task should not be left strictly to mechanical engineers are specialists, but should have heavy influence from the architect who can visualize the entire systems integration strategy. The Digiosk project combined geometry kit-of-parts components with motion primitives to produce a deployable structure that changes its configuration at various stages of use (Figure 2).

Figure 2: Digiosk robotic deployable kiosk

4. Design Principles

Combining Kit-of-parts Theory and automated construction concepts, we have derived nine principles for kinematic design:

Principle 1: Category : Kit-of-parts components can be joint-based (linear element), panel-based (planar element), module-based (solid element), deployable (time element) or a hybrid of these.

Principle 2: Strong Axis : Components, joints, and connections should be designed to take advantage of the direction of assembly or motion.

Principle 3: Seventh Joint : Components themselves can be designed as extensions to robotic manipulators so that they help in their own assembly.

Principle 4: Interface : Component connection strategies can also be used as grasp points for robotic assembly. Structure and infrastructure should have quick connect / quick release capacity.

Principle 5: Stackability : Components and major assemblies should be designed to stack against each other, so at least two modes of relationship between parts are defined: a storage relationship and a deployed relationship.

Principle 6: Kinematics : Using simple blocks of motion consisting of translation and rotation, complex behavior can be attained through nesting and combination.

Principle 7: Work Cell : Each component has its own behavior, whether kinematic or static. The envelope of motion is the work cell. Collections of component work cells have collective behavior that define a larger work cell. The entire building as a mechanism has its own work cell.

Principle 8: Hierarchy : All subsystems in a building are based on a double tree structure. Asymmetrical tree systems have supply and return, and symmetrical tree systems, such as structure, spatial hierarchy, and human circulation systems, are equal on both sides.

Principle 9: Grammar : Definitions of kit-of-parts component primitives and their assembly rules should be consistently applied without exception. Primitives can be geometric primitives or motion primitives.

5. Conclusions

By understanding how both physical elements and simple kinematic motions can be treated as primitive building blocks, we will be able to design an enhanced kit-of-parts building system that optimizes flexibility and robotic self-construction. Analyzing precedent, nine principles of category, strong axis, seventh joint, interface, stackability, kinematics, work cell, hierarchy, and grammar were derived as key attributes in a fully kinematic construction system.

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