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Grammars, Design and Assembly in Building

Abstract

Descriptions of architectural designs in terms of building assembly operations are examined and the use of these descriptions for evaluating automatic construction considered. Descriptions are generated using a grammatical formalism consisting of shape rules based on the spatial relations between components. Similar rule based descriptions can be given for architectural composition as well as the variable spatial relations in the robotic assembly devices. The design task is seen as primarily one which uses the interrelationships between these various rule based descriptions. The development of CAD systems which incorporate such a multi description formulation is examined briefly.

Introduction

A wide range of spatial relations are realized in the assembly of buildings from components. These relations vary from fixing pipework, assembling steel framework, to inserting window panelling. The variety of assembly tasks within the confines of the building in progress is a major source of difficulty in the application of robotic constructiontechniques.

The access of robots and computer controlled assembly machines to the different assembly tasks will often be highly restricted. This paper will concentrate on the representation of assemblies and the spatial environment in which they occur. The assemblies correspond to spatial relations between components and aggregates of the spatial relations provide the environment in which the assemblies must be realized.

The assembly operations consist of the path of the component to its final spatial relation. These consist of both the fixing operation and the transportation to the site of assembly. The aim of this paper is to discuss the basis of a description of a building design which will be of assistance in evaluating the building for robotic construction.

This description is based on the ideas of spatial relations between components. The relations can be used to form rules in a grammar, whose rules are used to generate the building description. The strengths of such an approach are that the rules can be used to generate descriptions of different designs based on similar sets of spatial relations. A further strength lies in the possibility of providing links between the generation of building designs and the corresponding construction operations.

To this end the paper will consider a number of topics. First, the way that such grammars can be defined, second, the importance of inferring spatial properties which emerge as the designs are generated and third how these emergent spatial properties are used to evaluate a design for robotic assembly methods.

Spatial relations and grammars

A spatial relation between two components is described at an elementary level by the description of the shape of both components when in the required spatial relation. The decription is just a pair of component descriptions in a single coordinate frame. Thus for two components with descriptions S1 and S1, denoting the descriptions of their shapes in a single coordinate frame, can be represented by the pair <S1,S2>. Components can be moved in the coordinate system by the application of transformations. For a transformation τ, τS1 and τS2 represent the components S1 and S2 moved by the transformation τ in the reference coordinate frame. The spatial relation $\langle S1, S2 \rangle$ is the same as $\langle \tau S1, \tau S2 \rangle$. Different spatial relations are given by $\langle \tau S1, S2 \rangle$ and $\langle S1, \tau S2 \rangle$. A spatial relation which is variable can be represented in the same way, where restrictions might be placed on the transformation τ. For example, a panel may slide on its fixing plates during positional adjustment, or special guides may be provided along which the component moves.

An alternative representation of a spatial relation may be given in which each object has a local coordinate frame which can be defined to make the description of that object convenient. The spatial relation can then be represented by a pair of object descriptions together with the transformation between the local coordinate frames. The description of the spatial relation is then not dependent on the position of the objects within the global coordinate frame. A spatial relation between objects S1 and S2 is represented by $\langle S1, S2, \tau \rangle$ where τ is now the transformation between the local frames. It would be counterproductive to describe the transformation in a global frame. By convention the transformation τ is described in the local frame associated with S1.

Objects can be transformed by moving the local coordinate frames. The moves of the local frames are described by transformations. Thus an object S1 subjected to a transformation α has a new description, say $\alpha(S1)$, where the transformation α is defined in the local frame of S1. In effect the transformation moves the local coordinate frame on the object. In general, the spatial relations $\langle S1, S2, \alpha \rangle$ and $\langle \beta(S1), S2, \alpha \rangle$ are distinct. However, if the β is a symmetry transformation of S1 ie. $\beta(S1)=S1$ (denoting equality of descriptions) then the two spatial relations are the same. Thus objects with symmetry give rise to multiple ways to realize given spatial relations.

These observations on symmetry may be phrased in another way. The spatial relation $\langle \beta(S1), S2, \alpha \rangle$ is equivalent to the spatial relation $\langle S1, S2, \beta * \alpha \rangle$, where $\beta * \alpha$ denotes the composition of transformations. Note that the transformations all take place in local frames and that the notation $\beta * \alpha$ means that transformation β is applied before α. However, for a representation of this composite transformation with respect to the initial local frame it is necessary to apply α first then β.

The spatial relations $\langle S1, S2, \alpha \rangle$ and $\langle S1, S2, \beta * \alpha \rangle$ are the same if β is a symmetry transformation of S1. Similarly, $\langle S1, S2, \alpha \rangle$ and $\langle S1, S2, \beta * \alpha * \gamma \rangle$ are the same if β is a symmetry transformation of S1 and γ is a symmetry transformation of S2.

A spatial relation $\langle S1, S2. \alpha \rangle$ forms the basis of a rule which replaces a shape S1 by the combination of S1 and S2 in the relation specified by the transformation α. This is an additive rule. Other rules can be based on the same spatial relation, such as the removal of S1 or S2 from a pair of objects which are in the spatial relation $\langle S1, S2, \alpha \rangle$, or in one of the equivalent relations if either or both of the shapes possesses symmetry.

The use of rules derived from spatial relations is the basis of shape grammars(Stiny 1980, Krishnamurti 1980, 1981). In these grammars objects are described as configurations of line segments and labels or markers. Rules are used in both the additive and the subtractive modes. Current implementation of such grammars deals with 2-dimensional shape representations (Krishnamurti 1986) but current research is aiming for an implementation using 3 dimensional shape representation, again using line segment descriptions (Krishnamurti and Earl 1986(forthcoming), Earl 1986).

In general the formalization of the spatial relations in terms of rules allows designs to be generated with the specified spatial relations between the components. Components are added or subtracted if the correct configuration of components specified by the left hand side rule shape is present. The shapes on the left side may consist of assemblies of objects which are to be altered by the application of rules. Further, there may be configurations of labels or markers attached to shapes whose type or configuration is to be altered by the rule. These rule can be used to control the generation.

The formalization of design possibilities by rules in a grammar can be based on the spatial relations which define the context of each component added to the building design. This will only be a partial context in the sense that it will be defined by features of the design selected in the left side of the corresponding rule. The context is defined by local spatial relations, and the power of a grammatical approach to generate possible designs lies in its ability to realize allowable spatial relations between components. However, in any design problem it is not just the local spatial relations which must be realized, the aggregates of these local relations must satisfy global conditions.

The rules in a grammar may sometimes be designed with appropriate labels in order to guide rule application to realize specified global conditions. This is the approach that has frequently been used in the application of shape grammars to architectural and building design (Stiny 1980,Koning and Eizenberg 1981). In this approach the rules are carefully constructed so that designs are guaranteed to satisfy conditions on their arrangement and spatial properties, perhaps elucidated from from the corpus of designs being generated or from other descriptions of the designs in terms of architectural intentions, functional requirements or explicit formal restrictions on the possible design, such as symmetry, layout, circulation or access properties.

Worlds of design

The creation of worlds of design is a central aim of work in computer aided design when considered from the the grammatical point of view (Earl 1986). These worlds of design encapsulate formal possibilities and are based on spatial relations between components expressed in terms of shape rules. For building construction the appropriate worlds of design are based on the relations between components. Particular types of building and construction techniques may be described by sets of spatial relations between the components. However, the problem of using such worlds of design is that the properties of designs in a given world are functions of the aggregates of components generated using the grammatical rules. It is these aggregates and their spatial properties which define the environment for robotic construction.

Spatial properties of designs

The general question considered here is the evaluation of the building design as it is being constructed. The process of construction may be mirrored at the design phase by the shape rules applied. The description of the building is given in terms of rule sequences. For construction the primary interest is in the partial descriptions as the building progresses and the identification of emergent spatial properties.

The emergent spatial properties of interest are those of the spatial context for the realization of a relation. The building provides a set of spatial constraints under which each successive construction operation is applied. These constraints belong to two broad categories. First, the access and passage of components to their final positions and second the provision of automatic or computer controlled machinery to locate the components. For the latter there are two further considerations; the transfer for fixing and the fixing operations themselves.

Evaluation for robot construction

There is a considerable task planning process (Lonzano-Peres 1982) within the overall design process. The aim is to plan the actions of robots or computer controlled equipment and to evaluate the suitability of different designs and sequences of construction operations for robot construction. This paper does not present a detailed examination of robot operations but will examine the possible advantages of a rule based approach to spatial descriptions.

The process of evaluation depends on the partial descriptions of the design at each stage of construction. In order to assess sequences of building operations it is necessary to infer the spatial properties which result from different sequences of rule application. In this way it should be possible to assess different sequences of construction operations without having to apply the rules explicitly.

The description of the building construction is not the only application of shape rules. For automated construction operations the equipment to implement the corresponding shape rules will be an integral part of the construction as it proceeds. This equipment will be characterized by a substantial range of motions and dexterity. There will be frames for the transfer of components and mobile mountings for the robots which effect individual assembly operations.

It is in the spatial integration of these machines with the building as it proceeds that the description in terms of rules and relations will have a critical effect. Possible machines, their spatial characteristics and possible locations may all be expressed as sets of spatial relations between elements of the machines, between machines and building components and between machines and aggregates of components.

It is instructive to look at the spatial descriptions of such machines and those of the building as two distinct descriptions which are brought together in the design of buildings for automated assembly. The descriptions should be compatible, but it is the relationship between the descriptions which determines the particular nature of the design task. The kinds of machine which can be used are dependent on the spatial properties of the design and conversely the spatial properties of the building, in terms of sequences of spatial relations are dependent on the kinds of machines available to realize them. This interdependence implies that it is essential to understand the consequences of generation in each rule system for the other.

The spatial properties arising from each of these generative systems will act as input to the other. Thus a particular building configuration will both constrain and be dependent on the kinds of machines and their possible motions. A system to aid design and evaluation of buildings for automated construction must be able to communicate the ways in which each generative system influences the other. The proposal to use a grammatical formulation allows the exploration of possible designs both for the building and for automatic construction machinery.

Variable spatial relations

As mentioned previously the spatial relation used in rule based spatial descriptions may be variable. This variability is essential for describing the motions of construction equipment as well as the motions of components in realizing final or goal spatial relations. The incorporation of variable relations in rules for generative systems is a current research problem. The shape grammar formalism (Stiny 1980, Flemming 1981) is adequate for stationary forms of the finished building, although the description of emergent spatial properties remains problematic. For variable relations these emergent spatial properties become critical since the variability both allows a range of emergent properties and previously prescribed spatial relations may inhibit the stated variation, perhaps because of collisions between components. Further, the variable relations in a rule may specify a relation between two objects which already have conditions on their relations given by emergent spatial properties. For example a transfer device mounted on on the building structure might be required to place a component in a given position within the building. The relation of the components and the building is given by a composite variable relation defined by the transfer device. To place the component as required, implies that the spatial relations within the transfer device are constrained. If a particular move of the component is needed then similar constraints are generated. Thus the application of variable spatial relations will require the analysis of the effect of relations on one another. This dependency among relations is addressed by the spatial inference system RAPT (Popplestone et al 1980). The use of such an inference system in combination with rule systems for generating assemblies of shapes will be required for evaluating how goal spatial relations can be realized in terms of subsidiary goals and intermediate spatial relations.

Architectural and building descriptions

This paper has made the case for considering the description of building designs by shape rules. This allows the generation of possible designs. Shape grammars have been sucessfully applied to the spatial descriptions of buildings and their layout (Flemming 1981). This work has concentrated on the composition of areas and volumes. It is proposed here that this approach is appropriate for the description in terms of the composition of building components and for evaluating automated methods of construction. This is an example of multiple descriptions both using a grammatical formalism. The construction operation description is an intermediary between the architectural spatial description and the descriptions of machines for construction.

Each of these descriptions is rule based and in a sense will encapsulate design knowledge for classes of designs, although much of this knowledge will be brought to bear in the ways that each of the rule based descriptions are used. This knowledge will concern the relartionship of the different descriptions. The relationship between the architectural description and the building construction description will be examined briefly.

In many examples of architectural composition, to which the ideas of shape grammars have been applied the design has been generated from arrangements of areas and volumes, leading to more detailed design work as the as the generation progresses. For example the facade articulation will often be seen as a set of rules following the outline generation of the facade geometry. However, the construction description will initially incorporate substantial elements of the facade geometry leaving final window and door detailing for the next construction phase.

The two descriptions of the building design are radically different and traditionally they would be seen as sequential. The architectural conception forms the specification for the generation of the building construction description. However, the architectural description will be generated with varying degrees of knowledge of available methods of construction. Although the primary design may take place with respect to the first description an evaluation of the design for construction requires the second, building operations description. Rule based descriptions allow the consideration of possible designs in each of the descriptions. The processes of generation are made explicit and offered as choices within a computer aided system incorporating rule based descriptions.

The shape grammar description as currently implemented deals only with shapes composed of line segments. This description is now being extended to 3 dimensional shapes and the implementation is being written in Prolog (Krishnamurti and Earl 1986). The main feature of this system for shape generation is that a partial design is searched for configurations of lines or shapes which match the left side of specified rules in the grammar. All possible applications of the given rule can be located without the need to match explicitly named instances of the shapes. In other words the recognition applies to shape features and not to the names attached at a previous stage to those features. This aspect is examined at length in a paper on the relation between shape grammar implementation and the development of a shape editing system (Krishnamurti and Giraud 1986).

Robot construction

This paper has avoided a discussion of particular robotics operations and has concentrated on the methods of modelling and evaluation of a building as regards the methods of construction. It has been argued that this requires a knowledge of the changing building geometry and the spatial relations which emerge as the construction proceeds. Further, such evaluation and the subsequent choices for design and construction depend on the ability to generate possible building designs, sequences of construction operations and the configurations of automatic construction equipment.

The general class of assembly operations in construction will require a new range of robot machines, both as regards payload, mechanical structure and sensing capabilities when compared with current industrial machines. In general an extensive use of teleoperated machines will be expected as a first stage in the automation of construction operations. These machines will fall into two broad classes. First the large scale transport devices for bringing components to their assembly positions. These machines will be a mix of special tracks and gantry like frames, cranes and autonomous guided vehicles. Second, there are the assembly and fixing devices proper. These may not require large ranges of motion but must be dextrous and accurate both for specific tasks and for ensuring sufficient flexibility between tasks. In this context it would be appropriate to investigate further the application of multiple loop and parallel actuated robot configurations (Earl and Rooney 1983, Hunt 1983).

The description of building in terms of spatial elements and the relationships is appropriate not only for evaluating robot assembly but also for planning the robot actions. Knowledge about the environment within which the robot is working is essential for sensor guidance. This knowledge may be expressed by the spatial configurations arising from the shape generation rules. The features for recognition and matching by the sensors may arise naturally from the shape generation, rather than the features being extracted from the spatial description of the building.

Development of CAD

This paper has argued for the power of a rule based description of shape for design and the automated construction of buildings. This enterprise is still in its early stages and requires a radical reorientation of the kinds of CAD systems available. A CAD system of this type incorporates rules of generation for shapes and then expresses possible designs within this rule system, rather than allowing the designer to move directly to the complete description of a single design solution. Such a CAD system is thus aimed first at enabling the designer to set up a world in which the processes of synthesis and evaluation will take place. The characteristics of these worlds will vary between application areas but it has been argued (Earl 1986) that in the field of architectural design shape generation is the major and defining thrust, rather than a function led approach to descriptions which might be appropriate to other areas of engineering design (Popplestone 1984). Indeed the relationship between functional and formal descriptions of designs is a critical area of research in the application of rule based systems in design. Recalling the earlier discussion of the different descriptions of the building design it is proposed that the essence of the processes of design is the relationship between descriptions.

The development of this type of CAD will require further investigation of the ways that more complex spatial elements than line segments can be incorporated in the shape grammar formalism. At present there is no explicit way of representing planes, surfaces and volumes. There are two problems. First the description of these spatial elements in the rules and second the automatic recognition of configurations of these spatial elements for rule application. The main problem here is the recognition of emergent spatial configurations. The current shape is searched for possible matchings. These give rise to the generation of possible designs, allowing evaluation and choice among the designs produced by the given grammar.

Conclusion

This paper has made the case that spatial relations are central to the description of building in terms of construction operations. The configurations and possible motions of automatic transfer and assembly machines may also be described by spatial relations, possibly variable. These spatial relations may be used as the basis of a grammatical formalism for possible building descriptions using construction operations. The relationship between these two grammatical descriptions provides the means of examining possible building configirations and methods for their automnatic construction. The assembly operations may be defined as spatial goals and constraints in the passage to these goals. These constraints may be expressed by intermediate spatial relations between parts already assembled in the building. This research is aimed at a reorientation of CAD to deal with possible designs, their generation and evaluation. Most importantly it provides a common base for the various descriptions of architectural designs required at different parts or levels of the design. Further it provides ways of evaluating the design for the integration of transfer and assembly equipment for automated and semi-automated costruction.

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