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BUILDING DESIGN FOR ROBOTIC ASSEMBLY

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ABSTRACT

Construction projects contain a high manual input in all aspects of assembly. Manufacturing applications of robotics, particularly in flexible assembly demonstrate the importance of design for assembly. This paper argues that attention must be focussed on building design if the potential for robotic assembly is to be realised in construction projects. Three areas are addressed. First the assembly operations. Second, the developing environment of the building in which these assembly operations take place. Third, the creation of formal methods for cost effective site layout to facilitate robotic assembly. Methods of rule based generation of building descriptions will be examined. The development of such descriptions of building designs offers the potential for effective planning for robotic assembly because the building design descriptions are created in a way which 'parallels' construction operations required for their realisation.

1. INTRODUCTION

To meet the demand from clients for continuing programmes of building - housing, schools, hospitals, libraries, offices etc. it is necessary to reconsider the methods used in the design and production of buildings. This is particularly appropriate at a time when a new young industry is emerging and provides increased opportunity for changes in traditional methods of working including the industrialisation of components both on and away from the site. It is essential to reduce the duration of projects and reduce the labour intensive nature of the industry due to the cost and difficulty of finding appropriate labour. For this to be effective it is essential that the designer has a much greater understanding of production needs of buildings and the potential of linking computer aided design to on-site use of robotics is an attractive one.

It is likely that the principal units used in any form of construction will be floor slabs, staircase units, balconies, lift and stair shafts, refuse shutes, external wall units.

The intention of this paper is to explore the implications of the wide range of on site assembly operations in building construction and to examine ways in which the introduction of automatic and robotic methods of assembly affect the procedures for building design. It is argued that robotic assembly implies the need to examine building assembly operations as central to the design of the building.

The foundations of the relationship between design and automatic assembly have been examined in the field of manufacturing (1). The problems of flexible assembly systems have centred around the appropriateness of the design for robotic assembly. Robots are considered a vital part of such flexible systems because of the variety of manipulations which they can provide.

Assembly operations represent a concentration of manual tasks which have proved difficult to automate. Problems are compounded from basic considerations of cost, time and technical feasibility. The nature of the assembly operations lie at the heart of these problems. They are not concerned with the operations on a single component as is the case with machining but will bring aggregates of components together in specified spatial relations. These relations may be complex and their successful execution depends on many properties of the assembly design including lead in features on components, partial obstructions, the criteria for recognising when assembly has been completed and fixing methods.

In addition to the complexity of individual assembly operations are the problems of intricate sequences of these operations to complete the assembly. This problem is generally overcome by passing the partial assembly between robotic workstations designed specifically for implementing a particular type of assembly operation. This solution essentially avoids the introduction of flexibility and is often applicable only to large batch sizes and relatively constant products.

Many of the concerns of robotic assembly in manufacturing are similar to those of construction. The need for complex manipulations, sensors to determine the states of an uncertain and changing environment and the intelligence to make plans for action and recover from errors. Assembly in building construction does not offer the means to structure the assembly tasks to minimise these problems. The stationary nature of the building implies that components must be brought to assembly locations rather than sub-assemblies moved between assembly stations. In effect the assembly stations are moved around the construction site creating the need for autonomous site navigation not necessarily present in manufacturing applications. Further, the construction site is generally poorly structured with little control or explicit knowledge on the locations of equipment and components until they are finally in position on the building.

The comparison of building and manufacturing assembly implies that the design of assemblies, critical for successful automatic assembly in manufacturing, is even more so in building construction. The design of assembly components in terms of desirable component features for robotic assembly is not the main purpose of this paper which is to present the means by which the overall design of the building may facilitate robotic assembly.

Small changes to design practice in terms of component design and choice are only a minor consideration in this aim which rather seeks to expose the need for building designers to think more formally about designs in terms of assemblies of building components. Consideration of building designs in this way will not only allow attention to be focussed on assembly operations to put individual components into place, but also to include the delivery and transfer of the components and the robotic devices used in the assembly, to the site of assembly.

The introduction of robotic methods of assembly provides the opportunity to reassess the procedures and methods of design. This lesson has been learnt in a piecemeal fashion in manufacturing assembly. The effective and productive use of automated construction equipment is critically dependent on the nature of the building design at all stages of construction. It is the changing environment of the building design during construction that presents the major problems for robotic automation. The designer should be formally and explicitly aware of the stages in construction of a design. It is only in this way that the designer can make realistic decisions on the suitability of the design for robotic construction.

There are three levels at which the designer should consider the building design for robotic assembly. At the lowest level are the specific operations required to bring the components together. Second the developing nature of the building during construction. Third, the wider issues of site layout concerning the number, location and delivery of materials and components.

2. ASSEMBLY OPERATIONS

Research on the nature of assembly operations considers the stategies for the successful completion of single tasks (2). This work is largely confined to manufacturing assemblies. However, there is little knowledge on the assembly stategies for construction assembly operations. Specific design features, such as uni-directional assembly, lead in features and snap fixing methods have been identified for manufacturing assembly. Although, the considerations for building design for automatic assembly may be similar the relationship of these operations in assembly sequences is quite different in construction. Manufacturing assembly tends to be concentrated around a single identifiable product but in construction some components comprise the building 'frame' but most are placed on and fixed to this frame. A building assembly system will need to move over the frame between assembly operations. The robot will need to move itself to new locations.

Knowledge of building assembly operations is required by the designer in order to design for robotic assembly. Understanding the capabilities of automated assembly equipment is required at the design stage. This knowledge is often available in the field of component manufacture using CNC machine tools, but is rarely so in the assembly of components which has been predominantly a manual operation. The flexibility inherent in these manual assembly operations has led to little consideration being given to the assembly operations at the design stage.

Building design thus requires an input on the characteristics of assembly operations if the robotic assembly methods are to be used effectively. It cannot now be assumed that all assemblies are equally difficult to make. The investment in, and availability of automatic assembly machines will limit the kinds of assembly which can be incorporated in a design.

It should not be assumed that this will necessarily introduce considerable constraints on the nature of the overall design scheme. In many cases the effect will be to place limits on the component details particularly in the methods of fixing, the geometry of mating surfaces and the types of manipulations needed to bring the components into the final spatial relations. The limits may not affect the overall spatial properties of the components.

The attention to these detailed features of the building component design specifically concerned with the relationships between the components will have the effect of increasing the designer's awareness of the importance of the spatial relations among the components of the building. Assembly is the business of realising these spatial relations. The problems of assembly are essentially about the passage through a sequence of spatial relations as one component is moved into its final position relative to another. The strategies for robotic assembly are expressed in terms of these sequences of intermediate spatial relations, which represent subgoals in the path to the goal of final assembly.

In order to consider the relation of building design and robotic assembly it is not sufficient to examine current component types and their assembly. As in manufacturing the problems of robotic assembly are as much about the design of the robotic systems as the design of the assemblies to make them suitable for robotic methods. The building design process must therefore adopt methods and procedures which produce designs appropriate for robotic construction. The emphasis should be on the ways that components are brought together to form the spatial and functional characteristics of the whole building.

The concentration on automating individual assembly operations has been identified (3) as a shortcoming in the development of robotic automation in construction. The examination of rule based systems arising from assembly operations will enable the planning of robotic methods of construction at the design stage, as well as the integration of these methods in the construction process.

3. DIMENSIONAL COORDINATION

If robotic construction is to be effective then it will be necessary to establish rule based generative systems for building design, based on the spatial relations among components. Rule based systems have the potential to ensure that dimensional coordination among the components in the design is maintained. The rules can be used to encapsulate a system of dimensional coordination for arranging the dimensional framework of a building so that components can be used within the framework in an inter-related pattern of sizes. To do this it is necessary to establish a rectangular three dimensional grid of basic modules to which the component will fit. The first step in producing a rational system capable of robotisation is to agree the basic dimensions of the enclosing fabric of the building at the design stage. The principle of relating components to a planning grid are not new and there are a number of British Standards which give recommendations for controlling limits to the dimensions and sizes for the structure and components. A process of dimensional coordination supposes a complete and careful appraisal of precise requirements at the design stage and decisions cannot be left until the building is being erected.

Dimensional coordination expressed as rules for design will lead to simplication of constructional details which will assist the mechanisation of construction both on site and in the prefabricated manufacture off site.

In order to take full advantage of the use of robots it will be necessary to adopt an agreed system of dimensional coordination, not only on a national but also an international scale. As part of this process an agreed standard of tolerances will also be an essential feature. This in turn presupposes a more comprehensive system of inspection and control to guarantee that manufacturing tolerances are maintained. The nominal dimensions of a component is fixed and indicates the zone in which the component must at all times fit.

The above considerations all lead to the requirements for design systems in construction which allow for the building to be described in terms of the assembly of components. The assembly operations incorporated into the design rules will be based on the examination of the nature of these operations and the strategies for their execution by robotic or other means. It is argued therefore that the need to design for efficient assembly on site using flexible robotic systems where appropriate, brings rule based systems of building design to the fore. This allows a formal description of the building in terms of the spatial relations among components and the spatial and functional characteristics of aggregate assemblies. In turn this allows the designs to be evaluated for robotic assembly and provides the input for planning construction. There are now pressing reasons to begin to formalise the nature of the building design process in terms of rules of design (4).

4. RULE SYSTEMS FOR BUILDING ASSEMBLY DESIGN

The examination of the importance of understanding assembly operations in construction has led to the conclusion that rules of design can be based on the assembly of components. The major advantage of such an approach lie in being able to ensure dimensional coordination within the rules used and in selecting those rules which correspond to robotically executable assemblies. However, it is essential to look further and examine how the generation of building designs using rule based systems should be guided and controlled to ensure design functionality as well as constructability. The problems here are considerable, since the application of individual rules can guarantee neither designs which meet functional specification nor sequences of assembly operations which are realisable, even though the individual operations are satisfactory. It is the combinations of rules which will have a semantic interpretation in the areas of function and construction.

Despite these difficulties the use of rule based design systems will bring the processes of design closer to those of construction, particularly the assembly processes on site. Designs will cease to be two dimensional formal compositions and become genuine three dimensional compositions of spatially related components. Design is thus no longer remote from the needs of construction in the same way that design and manufacture cannot be divorced in the progress towards effective manufacturing automation. The changes in building design arising from the introduction of robotic automation are not the central subject of this paper, but rather the framework and methods which are required to bring about these changes.

It is noted that the necessity of transporting the robot to the site of assembly as well as the components will impose more limitations on building design than the individual assembly operations. The rule based systems provide the appropriate tool to enable the examination of developing building geometry. This is the context in which the robot and components must move. These issues will be addressed below.

Before considering these, the development of rule based design formalisms will be traced. In principle the methods provide the means to explore design spaces by rule applications within the rule based system. The control and selection of generated designs may be based on a wide range of criteria ranging from the aesthetic to the functional. In the present context the designs generated will be evaluated against the methods and devices available for robotic assembly.

It has been demonstrated that the formal methods of the shape grammar implementation (5) of rule based design systems can provide the means to describe architectural design spaces as coherent aggregates of spatial relations among building elements. This work has led to a deep understanding of the meaning of architectural style. The focus of this research has been on aesthetic considerations. The main argument of this paper is that the natural derivation of design rules from construction assembly operations allows similar methods to be used in the exploration of design spaces for the evaluation and planning for robotic construction.

The thrust of this shape grammar approach to the description of building design in the creation of a design language whose elements are generated by the rules (6). The language of architectural designs may be thus generated from the spatial relations to be realised by assembly operations. Robotisation requires a design language to express and convey ideas of shape, size and consruction of the architectural components of an individual building or group of buildings. To have an optimum value the information conveyed by the language must be clear concise and subject to well defined interpretations.

The translation of a concept from a designer's mind into something that can be created by a robot is a complex process and involves a series of intricate steps which eventually converge as the designer incorporates many individual and diverse ideas into the complete and final design. The rule based approach will enable the steps in this integration to be formalised. Design and production of complex structures requires the solution of many complex problems. Construction projects may be composed of thousands of individual activities, each with a sequential or parallel relationship. The total design and production budget is often in the many million pound category and an economic method of designing that takes account of production processes must be seen as an essential facet. It is essential that provision is made for testing or simulating the final building at the design stage through the creation of a three dimensional model within a CAD system. It is argued here that the rule based approach allows the building design at all stages of construction to be evaluated and methods of robotic construction assessed.

5. BUILDING DESIGN AND ROBOT PLANNING

The rule based generation of building designs allows sequences of assembly operations which realise the spatial relations, incorporated in the rules, to be evaluated for robotic execution. The rules of design generation allow potential designs and sequences of assembly operations to be explored in terms of robot and component movements. The critical feature of a building design is that the developing design is the environment in which robot assembly devices are to operate.

To evaluate the design and plan for robotic assembly it is necessary to understand the emerging spatial properties of the design as the rules are applied. The problem here is that the spatial relations to be realised in assembly only represent a fraction of the spatial relations that arise from the rule applications. Spatial properties of the building design emerge as the design is generated. The design generation will be guided and controlled to produce some of these since they will form an integral part of the formal and functional specification of the completed building. However, many others will not be critical in meeting overall specifications but may nevertheless be important in providing information on the potential accessibility for robots and components.

Design generation in terms of available methods of robot assembly will require the addition of attachments for the robotic devices and the means of component delivery to the design. The means of robot support must be included in the design description.

The generative systems for building design will allow the overall development of the building on site to be examined because the design process parallels the development of the design on site. This is not just a means of simulating building development but of exploring the design space defined by the rules for solutions meeting functional and formal specifications as well as constructability criteria.

The design rules based on assembly operations enable sequences of these operations to be explored in terms of the emerging building geometry. Evaluation and choice is possible at the design stage, so that modifications to the overall design can be incorporated using backtracking procedures and the invocation of alternative rules.

The attention to automation of individual assembly operations is not sufficient to integrate robot assembly methods into construction (3). The developing building geometry and the environment in which the robot works must also be considered at the design stage. The robot environment on the construction site is often identified as a major difficulty. The robot moves to the site of assembly and components are delivered in a complex and uncertain spatial environment. The motivation for describing the building design in terms of spatial relation based rules is that knowledge of this environment is included at the design stage and can be used in creating well structured plans for robot actions.

Planning for robot assembly will require the spatial properties of large and complex aggregates of components which emerge from the rule applications, to be inferred from the sequences of rule applications. The process of design will require that the rule applications be controlled to direct the design generation towards those emergent spatial properties appropriate for robotic assembly. The sequence of rule applications corresponding to component assemblies must create at each stage a partial assembly on which the robots can work and to which both robots and components can gain access. The problem is therefore to specify the nature of the spatial environment for robot assembly, to guide design by this specification and to match emergent spatial properties against specification.

6. PLANNING AND CONTROL

The means to evaluate building designs for robot assembly have been sketched. Precepts and guidelines need to be established for movement within the developing building of robots, components and materials as well as access to building and the general organisation of site layout. This will allow the planning of the priorities and sequencing of construction operations and provide the control structures to implement the plans on site.

Site layout is dynamic and changes physically during each phase of construction. These phases are specified by activities and it is important to determine a series of central focuses in each stage about which other activities revolve. In particular, points of access to site or developing building will determine the focal points of activities. It is likely that in a particular phase one activity, for example, concrete work, may have a coordinating priority. This may occur in a number of phases and therefore, the focus of this activity should be within reach of casting and placing areas, within crane sweep for horizontal and vertical movements and have access to hoists for vertical movement.

Once ground work and substructure have been completed the next phase introduces vertical movement and robots may be used in conjunction with cranes and hoists. As work progresses site layout requires adjustment and becomes increasingly determined by the building geometry. Planning and control of the construction becomes more complex with wider spans of control, a more dynamic approach to communications between activities and a more intensive use of robotic assembly.

Access to the points of activity must be provided as the building geometry develops. Doorways and windows are often used, but temporary access routes for robots, materials and components should be provided at design stage. Careful planning should enable floor and wall sections to be temporarily omitted to allow access without affecting structural integrity.

The movement of materials, components and robots within the building is a major problem in robotic assembly. Guiding frameworks, rails and ramps will need to be incorporated for the duration of a construction phase.

7. PREFABRICATION

In drawing comparisons between manufacturing and construction in terms of design for robotic assembly the continuing interest in prefabricated components should not be ignored. Prefabrication has resulted from an examination of the difficulties of on-site assembly operations. In this way there has been considerable influence exerted on building design. Prefabricated components may still leave difficult assembly problems on site, particularly with the access and fixing of geometrically complex components. However, they do offer the scope for robotic assembly of those components either off site or in specially prepared workplaces on site.

The prefabrication option can be assessed along with other assembly methods in the planning and evaluation procedures applied to the building design. Prefabrication now represents just one route to guide the generation of building assembly operations. It is based on a decomposition of the building into functional components. As a design philosophy it attempts to reduce the interactions between components and as a construction method it removes many assembly operations from the complex spatial constraints of the developing building geometry.

Rule based design systems allow construction plans to be generated as the design is taking shape. Many different construction methodologies can be explored with their associated impact on possible designs. There is no need to be constrained by a single methodology such as prefabrication.

8. COMPUTER AIDED DESIGN

Methods of rule based design description have been advocated as most appropriate for the parallel generation of designs and their planning and evaluation for robotic construction. CAD systems for building design are generally used as a formal modelling framework for entering, recording and displaying the spatial features and characteristics of a design. This process involves the haphazard and informal applications of design rules and is generally structured according to levels of detail and types of service. The main purpose is to describe the design in all its complexity and to submit this for analysis of cost, structure, materials requirements, services and circulation. This distinction between formal design and functional analysis makes it difficult to assess a design for robotic assembly which requires that the stages of construction are available. Partially completed buildings are the environment in which the robot operates. Design evaluation for robot construction should be accommodated within the design process and be able at each stage to guide design generation. The CAD system for building design must therefore be able to accept and apply rules of spatial composition to generate assembly sequences for buildings.

These changes to the processes of design do not just deal with new ways of entering a design, previously formulated, into a CAD system or in structuring that information in a database for subsequent use in planning for automatic assembly. The thrust of the argument is that a rule based approach provides a structured approach to the examination of alternative designs in terms of assembly operations from which the rules are derived.

9. CONCLUSION

Building assembly operations can be used to provide the basis for rules to generate building designs. These rules are derived from the spatial relations between components and may be incorporated into snape grammars specifying languages of design. The design process can then include the evaluation both of individual assembly operations and the planning of sequences of those operations for robotic construction. The descriptions of building designs in this way allows the developing building geometries to be explored to aid planning and control of robotic assembly on site.

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