CONNECTIONS FOR CONSTRUCTION - A ROBOTIC APPROACH

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ABSTRACT

This paper proposes that the effective introduction of robots into building construction will require new techniques for component connections. A survey of current techniques used for the jointing of structural components through to the attachment of finishing panels indicates that few of these are adaptable to robotisation. Some alternative techniques are proposed which, despite their acceptance in other spheres of engineering, will require rigorous testing for their suitability and long-term integrity in the field of building construction.

DESIGN FOR CONSTRUCTION

The introduction of automation and robotics into the mechanical, electrical, and aeronautical engineering sectors has highlighted a common strength in these industries, the direct link between design and manufacture. Fast, efficient, accurate construction dependent upon automation devices has strengthened those links, shrouded them in all-embracing CAD/CAE software, and led to major rethinks in traditional materials and their assembly.

It may come as a shock to realise that the panels of our next car will probably be glued together rather than welded, but this is typical of the revolution in joining techniques that is taking place in these industries. The building construction sector, hampered by the traditional division between the design and construction professions, is at last facing up to these challenges. *'Design and build'*, *'Fast Build'*, and *'Fast Track'* are the current management and design techniques to improve construction speed and efficiency. The architectural profession, now having quite sophisticated CAD tools for their creative design work, are taking part in multi-disciplinary design production involving structural and building services engineers. The eventual extension of the CAD tools into CAE areas will strengthen these links.

Techniques for fast building programmes are becoming increasingly dependent on automation, and innovative ideas are emerging, especially in the area of *in situ* concrete frame construction. Bennett [1] describes advances in formwork systems using prefabricated panels (flying forms) which are reducing labour costs substantially and eliminating much material wastage. Climbing formwork, tunnel formwork, adjustable column forms, and prefabricated reinforment are all relatively new techniques which are gaining in popularity for fast build programmes, and considering the cure-time of the concrete medium, they probably represent the maximum reasonable degree of automation required for these processes.

The important principle here is that these automation techniques, however ingenious in their own right, are totally dependent upon their incorporation in the building design from the conceptual stages to acheive their efficiency. They all require:

- highly repetitive design, especially of floor layouts
- standardisation of member sizes, storey heights, and column dimensions.
- simplification of design using, for example, solid or ribbed slabs as opposed to waffle slabs which would prevent use of flying forms.
- reduction of site operations by using cast-in screed rails, pre-fabricated stop-ends, direct finishes for floors, etc.

None of the above can be incorporated after the design stage, and it follows that major savings can be acheived by *'Design for ease of automated assembly'*.

DESIGN FOR AUTOMATION

The motor industry was the first to apply *'Design for Automation'* (also known as *'Design for Assembly'*) methods, and they report significant financial benefits (Ford USA,1989). It is instructive to consider the reasoning behind these techniques:

- manual assembly costs continue to increase while component fabrication costs are reducing in relative terms.

- for many products the cost of assembly and related handling and inspection can exceed 50% of the component cost.

- integrated components generally lower the product cost. Design should aim to integrate adjacent components, and where possible simplify the resulting assembly.

- reduction in assembly work will generally have a greater impact on reducing product cost than any increase in the cost of component manufacture. Savings may be expected in the capital cost of automation equipment, reduced inter-process handling, and improved product quality.

Designs are rationalised by examining the potential of every component to be integrated with its neighbour. If the material of a component is (or can be) the same as its neighbour, and there is no relative movement between the components, then it should, if at all feasible, be combined.

The above rationalisation process reads as a series of logical tests, serving to indicate the potential for applying expert systems methods to such design processes.

'Design for assembly' involves further tests aimed at reducing manipulation to a minimum. These question the need to turn components over during assembly, whether gravity can be used in the assembly process to stabilise sub-assemblies, and whether all processes can be carried out in a single chosen direction in order to minimise the number of robot axes required. The orientation of a component as delivered to an automation device has to be recovered for automatic assembly, and in a worst case may require the complexity of a dedicated robotic system using vision aids to acheive this.

Regarding the supply of correctly oriented components to machines, the electronics industry is probably furthest ahead with its standardised component packaging for automated assembly. These include plastic protective slides for Dual Inline Packages, waffle packs for Surface Mount Devices, and bandoliers for axial components such as resistors and capacitors.

Common component handling problems in the electronics industry and in automated building construction might not be apparent, but the principles of recovery from lost orientation apply generally. Identification of unique features on the component is first necessary, followed by reorientation to the required state. Both of these processes require intelligent handling devices.

A further handling concern that deserves consideration at the design stage is of robotic gripping. Jaws and grippers are complex and expensive parts of a robotic system, and reduction of their complexity by designing in easily gripped surfaces is often possible.

AUTOMATION FOR MANUFACTURING AND CONSTRUCTION PROCESSES

As already noted, *'Design for automated or robotic assembly'* constitutes an opposite pole to the traditional contracting system which represents the bulk of building production today - Brown [2]. Recent large scale projects have reported success in the use of CAD coupled to *Fast Track* construction, and it is clear that although there is still some fragmentation of the through process due to sub-contracting, intervention at the design stage for assembly considerations is now a possibility.

Before embarking on a programme of automation/robotisation anticipating only cost savings and perfection, constructors should consider the impact that such an approach requires on the traditional approach to building. Robots are particularly bad at mimicking human tasks - Wing [3] and their successful application is totally dependent on use of robot-oriented design principles from the start of design - Bock [4]. Here again experience from other industries can serve as an example:

- The number of robots installed in the UK electrical/electronics industry fell by 63% in 1988 compared to 1987 (figures from British Robot Association). Two reasons explain this - Surface mounted devices require great precision in their location, beyond human capability. Robots are slow when working at such precision, and dedicated mounting machines have taken over these tasks. This is a reasonable choice of more suitable technology, but the second reason is more generally significant: Dwyer [5] reports that the *'barrier to assembly automation is that products are not designed for it...by the time a company has redesigned a product to make it simple enough even for a robot to assemble, humans make an even better and cheaper job of it.'* This conclusion is somewhat dependent on UK labour costs remaining at about 2/3 of those in competitor countries, but nevertheless illustrates the delicate economics of automation and the fundamental importance of *'Design for assembly'*.

- Taylor [6], also reporting on the fact that manufacturing industry is buying fewer robots than predicted, concludes that the use of robots is becoming concentrated where employers find it hard to recruit and retain humans to perform dirty, repetitive tasks such as welding, gluing, sealing, spraying, and finishing....they will be a necessary assistance, not an alternative, to humans in the manufacturing systems of the future. Significant is the emphasis on jointing techniques.

Some stages of building construction, especially those for steel or concrete frame construction, will be unsuitable for robotic devices by virtue of the heavy payload requirements. Developments based on telescopic cranes using teleoperation principles are likely to succeed here. Andeen [7] highlights the different requirements for heavy construction tasks to the position control requirements of manufacturing industry. Industrial robotic manipulators will find their place in finishing processes for construction, and for detailed assembly tasks. The same *'Design for assembly'* principles, however, apply of the whole range of tools - robots, automation machines, and teleoperated devices.

THE JOINTING APPROACH

The current state of development of construction robotics appears somewhat piecemeal, and is concentrated in relatively few research centres. This is inevitable, as much of the enabling technology for the necessary robotic tools is still several years away, and there are limitations to current techniques.

As the preceeding sections of this paper have attempted to demonstrate, the successful use of automation and robotics is linked to product design, and whilst awaiting the 2nd generation robotic tools it is necessary to look hard at robotic design potential in this industry.

A *kit-of-parts* approach to automated construction is being advocated by several researchers. More important from a robotic design standpoint would be a *kit-of-joints* to satisfy *'Design for assembly'* objectives. A programme of design investigation is proposed by the author using *database* technology to seek promising techniques for robotic jointing, the fundamental key to robotic assembly. The sweep for methods should include worldwide construction methods, and be extended as far as possible into other industries in the search for promising jointing techniques.

The assembled *database* would provide an ideal reference point from which to investigate new techniques, and should stimulate a cross-fertilisation of ideas at an international level. There is no doubt that robotic methods will require changes to traditional jointing concepts in addition to a need for new materials. Increasing automation for assembly tasks will be coupled with more extensively automated production of building components both on and off site, which will result in new materials having qualities matched to robotic handling and assembly.

There are surprisingly few basic jointing methods, but stemming from these we find a profusion of derivatives. Jointing is three-part assembly process: *Positioning / Fixing /* and *Protecting* - Martin [8].

Positioning involves the handling and orientation processes described earlier. Orientation and positioning are potentially complex and expensive operations for robots. In many instances design can provide the means for relative positioning components without the necessity of vision or other advanced systems. Design attention to the axes involved can also reduce robot complexity; if layered assembly, use of gravity, and correctly oriented part delivery principles are employed, three axis robots should be able to handle most jointing requirements.

Fixing is the aspect of jointing most likely to change radically with automation and robotisation for building construction. This process can be subdivided into four categories :-

Connection represents the joining of parts by a jointing section such as a dowel, nail, or pin. Of the four categories of fixing, this is the least amenable to robotic techniques, as the joint is reliant on driven or percussion assembly for its success. The extensive reliance of construction methods on driven connections would indicate that this is an area open for extensive design method changes.

Fastening is a method of fixing using jointing components such as screws, bolts, and rivets. Screw and nut assembly can be difficult to automate, as apart from the component feed problems, screw starting and thread bottoming are serious complexities.

Robotic riveting has received much development in the motor and aircraft industries, and is in general a simple robotic task. Its use in building construction is, however, limited due to the heavy sections used in this industry.

Snap fastenings have become very popular in the mechanical and electrical industries, using pressed steel or plastic fastenings. As yet these have found very little application in building, but must have great potential for automated assembly of components such as finishing panels.

Locking is a method requiring that adjacent components be designed to interlock without an intermediate jointing component. The technique is potentially ideal for automated assembly, but not possible to apply widely. Ingenuity on the part of the designer is required, as this represents the most severe test of the *'Design for assembly'* method.

Adhesion is a large class of fixing methods that includes glueing, welding, and the wide range of cement based fixing methods for bricks and tiles.

Welding robots are as yet not well adapted for on-site usage, although they are finding application in factory prefabricated assemblies, and MIT are now demonstrating a promising robotic adaptation of the stud welding gun for shear connectors - Ziegler and Slocum [9].

Cements, in so far as traditional mortars for masonry construction are concerned, are likely to be replaced by adhesives. For automation it is necessary to have a ready mixed adhesive that can be dispensed easily by machine and that has predictable properties. Lehtinen [10] reports a robotic masonry system where the bricks are dipped into such an adhesive as the application method.

Probably the biggest advances in jointing technology in recent years have been in adhesives and their automated application. Davies [11] describes developments in the motor industry where adhesives are replacing traditional spot-welded methods for door panel assembly. Curiously, the motives behind this change are not only for product improvement with respect to rattle-proofing, rust-proofing and precision of alignment, but primarily to avoid the unsightly surface blemishes produced by spot-welding which waste time and material in subsequent paint cover-up processes.

Adhesion, unlike connection and fastening methods, is highly dependent on the nature of the components being joined, their surface characteristics, application method, and curing conditions. Widespread success of this method will be dependent on extensive research and development.

Protection, the final operation in jointing, is intended to provide environmental protection of the joint, and involves the use of sealants, fillers, flashings etc. The application of all these protections have excellent potential for robotisation. It is interesting to note the use of a fibreglass-reinforced bonding cement in the automated construction of concrete block walls - Killen [12], where surface bonding of this material provides both the adhesion and protection requirements.

SUMMARY

The brief and much simplified survey above represents a wide variety of jointing techniques being used in an even wider variety of applications. Few of these are suitable for straightforward conversion to automation or robotisation, but many are suited to alternative design approaches. The intended *database* study should indicate promising areas with potential for new approaches suited to automation.

The construction industry is pushing for improvements in productivity, speed of construction, quality, and safety. Automation and robotics can provide these improvements when conceived hand in hand with the basics of building design, and especially with the jointing processes. CAD/CAE design aids configured specifically for automation in building design and construction will be a key requirement.

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