A NEW DIRECTION IN AUTOMATING CONSTRUCTION

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ABSTRACT

The majority of work in the field of construction robotics has focussed on the adaptation of existing industrial robots to automate traditional construction processes that use basic materials. This paper introduces a new approach, that of construction based on a factory-produced 'parts-set' especially suited to a range of on-site purpose-designed robots, aimed at the provision of high-tech buildings. This approach is intended to deskill as much site-based work as possible as a counter-measure against the increasing shortage of skilled operatives and to reduce unit costs of production.

1. INTRODUCTION

1.1 The Progress in Construction Automation

The construction industry has been much slower to introduce on-site automation than the manufacturing industry, even though building is very labour-intensive and requires a wide range of expensive skills which are rapidly vanishing in the developed countries [1]. Accordingly, there are many incentives to examine the reasons for this and to propose strategies which might help to by-pass some of the existing problems. It must be borne in mind, however, that much work has already been performed in academic establishments with this in mind. Most of this work has tended to focus on the use of almost conventional industrial robots in traditional construction, for example, Blockbot [2], [3] has been developed for constructing sections of masonry block walls. The proposal seems to be technically sound, but appears to be an expensive and relatively slow way of constructing buildings. Another example is in the development of robots for traditional interior finishing tasks such as the building of partitions, and plastering or painting interior vertical surfaces. Technion's Multi-Purpose Interior Robot [4] is being developed with these applications in mind.

This piece-meal approach has even extended to the laying of foundations and the levelling of concrete flooring. For example, one research group [5] has developed computer-based models for simulating automatic excavation. This work is concerned with the modelling of robot structures based on an existing excavator back-hoe arm. The objective is to add intelligence to a conventional excavator, although retaining the operator. In another example, a device has been developed by Shimizu for concrete floor finishing and has reached the stage of extensive field-testing. Initial impressions indicate that this robot will soon appear on site to supplement existing 'power floating' equipment. Whilst devices of this kind will improve the efficiency of present methods of construction and remove the operator from particularly unpleasant and back-aching tasks, they do not contribute to the major change which we feel is necessary. Furthermore, we see robots in a supporting role in helping to produce buildings fit for modern industrial and commercial uses. Robots are thus a means to an end, not an end in themselves.

1.2 An Alternative Approach

In view of the obvious problems encountered in the automation of construction, it is now opportune to invert the problem. Instead of making robots match existing construction methods, we propose to make construction match the requirements for automation. The most obvious objection to this proposal is that such an approach might reproduce the notorious industrialised, low-tech concrete buildings of the 1960s. This would not be the case because it is possible to avoid the kind of errors that arose on 1960s buildings by combining the skills of architects and engineers. The priority must be to design buildings which are aesthetically appealing in both exterior and interior appearance whilst being structurally sound. They must also offer flexibility so that the interior layout may be altered quickly, and at low cost, to provide a satisfactory internal environment for users. It would be necessary to incorporate all the services (for example, heating, lighting, ventilation, power, communications, security and protection) as an integral part of the superstructure, and thereby provide the required degree of building intelligence [6].

Traditional construction, with its emphasis on the use of wet materials such as concrete, mortar and plaster, combined with small building components such as bricks and tiles, although apparently offering great flexibility for design, has several objections other than those concerned with automation. First, construction is slow and expensive and involves the use of scarce, skilled operatives. Second, the provision of services usually requires several operatives to work concurrently in inconvenient and confined spaces. The quality of the final product often suffers because the finer details are dealt with on an *ad hoc* basis by the operative. As the demand for improved services and intelligent buildings increases, the especial problem of adaptation is likely to become more acute and exacerbated by skill shortages. A third objection to traditional construction methods is that it is generally expensive and time-consuming to refurbish buildings; however the internal spaces of modern commercial and high-tech industrial buildings may need to be refitted periodically during their life times to cope with changing user requirements.

It appears to us that, at present, it is most appropriate to focus attention on the construction of one or two types of building, namely modern commercial and high-tech industrial. These buildings have simple structures of no more than two or three floors. They are often custom-designed, contain sophisticated services and are constructed fairly quickly. Additionally, they offer flexibility for expanding users whose requirements for office type accommodation are likely to change rapidly. Buildings must be designed from the inside out, if they are to fulfil users' needs [7]. Practical solutions are needed if interiors, in particular, are to have a useful life [8]. Part of the solution would be to make the life cycles of the 'shell and core', 'services' and 'scenery' truly independent. Thus, the easier it is to change the scenery without replacing the basic services or reconstructing the shell, the easier it is for a building to accommodate change. It is our objective to tackle the problem of the design and construction of these types of building from the standpoint of construction automation.

1.3 Design for Automation

By confining ourselves to the design of particular types of building, we can more readily apply the systems approach to construction, avoiding as far as possible, highly skilled on-site processes. Our method of approach is to rely on the use of a universal factory-produced 'parts-set' especially suited to a new range of purpose-designed construction robots. The aim of this approach towards factory-based production and on-site assembly and fixing is to reduce the unit costs of production, whilst deskilling site-based processes as a counter-measure against the increasing shortage of skilled operatives. To take full advantage of flexible manufacturing systems (FMS), it is essential to define the parts-set to include basic superstructure elements such as frame components and cladding and more complex, composite elements such as toilet pods and floor systems (complete with built-in universal services). Design of the complete parts-set for a building could be accomplished rapidly using computer-aided design techniques. Feedback from building owners and prospective users could be obtained and the design modified as appropriate.

The next stage of the design would be to produce the construction programme and the requirements for a set of mechanical construction aids which would normally include instruments, power tools, manipulators and robots including required software. Such a procedure would be supported by an expert system. The construction planner would be an automation expert who, in producing the construction programme, would specify the required tools using a computer simulation program (perhaps similar to ORBIC-1) [9]. The construction process could be planned, rehearsed, modified, optimised and checked quite rapidly. The entire method of assembly would then be documented as a full set of instructions to be used by on-site operatives and would also include any software necessary for programming the robots. The final step would be to produce a parts-list and a tools-list for the manufacturer. Again the computer would be used for this purpose. It would automatically review the design and the construction programme and by means of an expert system would produce a schedule for loading container-vehicles at the factory/warehouse. The required parts and tools would then be scheduled to arrive at the site 'just in time' for use in the construction process.

2. THE MODULAR APPROACH

2.1 Preamble

For the purpose of this new approach, modular construction is defined as an industrialised, component-based building system. The use of standard components from a parts-set enables the designer to specify buildings of many shapes and sizes. Individual components of the parts-set are designed with FMS and on-site automation in mind. A significant feature is the integration of the design and construction process through the use of generic CAD tools and the application of CIM concepts. Such an approach permits the transfer of much of the process of construction from the site, where working conditions are poor and subject to the weather, to the factory where quality control is easier and a wide range of manufacturing techniques is available. The concept of 'modular system building' is not new, the architect Le Corbusier [10] presented this concept at the beginning of the century. During the 1960s it was applied to high rise housing without much success. The reasons for the failure of systems building were due mainly to a lack of understanding of the psychological and aesthetic considerations implied in the use of this type of building. But also the construction of the buildings was of a uniformly poor quality. More recently, the Armenian Earthquake shattered buildings which were in principle correctly designed, but which were, in practice, quite wrongly constructed [11].

Thus, most of the problems which arose from the use of system building were due to poor workmanship, lack of quality control in the factory, lack of awareness of users' needs and the poor aesthetic presentation of the buildings. The implementation of this kind of technology was made more difficult because construction practices at that time could not cope with this new approach. Some of the difficulties presented were due to the pressure of erecting large numbers of high rise buildings within minimum time, a lack of experience of modular building systems and a limited technical knowledge at all levels from management down to site operative. It must be said that not all applications of modular building systems were failures. There are several examples where the approach has been used successfully, notably CLASP [12], SEAC [10], NENK [10] in the UK, SCSD [10] and Teckrete Systems [10] in the USA.

2.2 New Construction Systems for High-Tech Buildings

The new type of building system to be proposed in this paper is based on current component systems, the application of new developments in manufacturing, system building concepts and past experience. The basis of this building system is the parts-set which consists of structural components and elements that make up the external envelope and interiors. The structural components would strive for universal application, enabling a whole variety of enclosures to be built from a limited parts-set. The use of the parts-set principle can be based on four alternative system building approaches: structural frame plus customised cladding; cellular construction; cellular plus specialised cladding; and hybrid frame and cellular construction.

2.2.1 Structural Frame plus Customised Cladding

This system uses a set of prefabricated components, most of which could be customised, although all of them would have some common characteristics. The use of FMS would enable one-off components to be produced without cost penalty. The structural components of the parts-set include provision for cladding and services as well as detailing aimed at minimising assembly errors. The underlying assumption is the application of the 'design for automation' concept at all levels, as well as 'design for flexibility' which, in particular, would enable several kinds of cladding to be accepted. The structure could be erected rapidly and a weather-tight state reached more quickly than is presently possible with traditional forms of construction. The choice of cladding would be at the building owner's discretion.

2.2.2 Cellular Construction

This building system is made up of fully finished, preformed load-bearing cells or units which require no further work. The system requires site-connections only of units and services, that is, everything is built into the units in the factory. It is assumed that the units can be transported to site and then manipulated without much difficulty. The choice of cladding, the internal partitions and other elements used in the units are limited only by weight and aesthetic appearance. Cellular construction involves less time on site and provides a building which has the benefits of being produced under strict quality control conditions. The potential shortcomings of this system are the aesthetic appearance of the cladding, the joints between units, limits on the weight and size of units and the integration of individual units within the whole building. Additionally, service connections may prove difficult and expensive, and there is still a distrust amongst building owners and users of this kind of system building.

2.2.3 Cellular plus Specialised Cladding

This system is also made up of load-bearing cells or units, but without a supplied cladding so that the developer or building owner may choose his own. The aim is to provide a structure built up from units containing most of the building's interior. A feature of the design is that units on the perimeter of the building would allow for the application of the cladding to be carried out last. The advantages of this approach include high quality interiors with a cladding chosen by the developer or building owner. This makes the building look non-prefabricated and thus more appealing. By comparison to the basic cellular system, the one proposed here gives an improved appearance and better flexibility in use. Also, larger units can be used as their individual weights are reduced by omitting the cladding. This approach attracts similar problems to those affecting the basic cellular system, namely a restriction on the number of floors allowed and potentially difficult joint and service connections.

2.2.4 Hybrid Frame and Cellular Construction

In this approach, a structural frame is erected using the components described for the system in section 2.2.1. Afterwards, prefabricated units are slotted into the positions created by the frame. This approach enables the complete interior of the building to be constructed in the same way as if it were the 'cellular plus specialised cladding system', but without limits being placed on the number of floors allowed. The fixing of the units and the connection between services, as well as the erection of the structural frame, would be done hierarchically. The cladding is applied afterwards, giving a building with the same characteristics as those described in section 2.2.3. The principal disadvantage of the approach is that there will inevitably be constructional problems associated with locating the units within the structural frame. These difficulties can be resolved by careful scheduling of the construction programme, as has been demonstrated on recent 'fast-track' construction projects in the UK.

2.3 Characteristics of Modular Building Systems

The successful application of system building plus robotics depends on the inherent characteristics of the system, the basis of which is a parts-set [12]. The proposed system must:

1. permit the transfer of much of the construction process from the site to the factory;
2. standardise processes and components so that all operatives involved are familiar with the system;
3. allow closer project control with predetermined component prices and the possibility of serial tendering for work on-site;
4. make buildings more amenable and adaptable to user needs, thus extending the useful life of shells and, possibly, interiors.

Before defining the characteristics of the components of the parts-set, it is necessary to determine where the boundary between standard and special components should lie. Several factors need to be taken into account for each range of components [12].

1. The likely frequency of occurrence in the particular types of buildings selected.
2. The scale of production of the component overall.
3. The manufacturing techniques available and whether or not they are capable of providing a wide range of components without generating excessive cost or incurring other penalties.

The basic characteristics of the components of the parts-set are as follows.

1. They should not restrict unnecessarily the freedom of designers on individual projects.
2. Fixing mechanisms and measurement systems must be standardised.
3. A degree of redundancy should be built into the components to extend their range of application and support as many building types as possible.
4. As many components as possible should be multi-functional, that is, they should have more than one role within the building, for example, walls must not only be space dividers, they should also take some of the services.
5. The physical characteristics of components must take automation into consideration.
6. Information on each component should be stored in an object-oriented database enabling lists of the components and tools to be generated, erection times to be estimated and so on [9].

The list of characteristics given above allows a first level design of the robotic manipulators to be made.

3. ROBOTS FOR MODULAR BUILDING SYSTEMS

3.1 Preamble

Several research papers produced by academic establishments [1], [13], [14] and publications by construction companies [15] have pointed out the need for on-site construction robots. The application of automation technology and modular building systems present important opportunities for the industry: higher productivity, better product quality, greater flexibility in the use of building space, faster speed of construction and better value for money for developers and building owners. The incorporation of robot-oriented design concepts in the production of components of the parts-set [16], plus the adaptation of building technology for automation [17], makes the application of robotics on-site more easily attainable.

The following sections describe a family of robots which are designed to assemble and locate some of the components of the parts-set.

3.2 New Robotic Tools

The robots to be described below form part of a family of automatic devices that have some common parts between them. For example, all robotic tools that need mobility inside the building will use the same Autonomous Guided Vehicle (AGV) thereby reducing development costs. There must, however, be compatibility between the tasks that they perform, particularly the handling of components. Also, it is very important that, wherever possible, the tasks to be performed are complementary to one another. Eventually these robots would possess a common interface protocol like MAP to permit inter-communication. A Master Project Coordinating Program (MPCP) would generate the parts-list, tools-list and then control the scheduling of tasks and monitor their performance. The design of this family of robots cannot be separated from the components of the parts-set. Two distinct, but dependent, design criteria need to be considered. The first is concerned with the development of robotic devices and the second is related to the manufacture of components [18]. It must be stressed that most or all components would be manufactured using FMS techniques [19]. Components that are intended for manipulation using robotic tools need to be selected against rigorous criteria. It is also necessary to have a comprehensive understanding of issues such as material handling, sensor technology, system hardware and software, autonomous modes of operation and so on [20], [21], [22].

Other considerations must assess whether or not these robots have scope for use outside modular system building. Their use with some or, preferably, no modification on building projects that retain traditional construction practices would enhance market potential. This would also serve to make the use of system building and robotics by construction companies more acceptable. A further issue commonly overlooked concerns the logistics of material handling and the operation of robots on-site. The material handling issue, in particular, helps to define the characteristics of the robot and should not, therefore, be ignored.

3.3 Example Robotic Tools

The feasibility of applying this new approach can be determined by a range of criteria [18] developed specifically to help in identifying those components that can be fixed and manipulated by robotic tools. To illustrate the proposed concept, four processes that use robotic tools and components of the parts-set at various stages of the construction process have been considered: frame erection, floor laying, partition placing and cladding erection.

3.3.1 Frame Erection

This process consists of an automatic crane and a tracked AGV. The crane carries the load and makes coarse manipulations, whilst the vehicle directs the precise positioning of the structural component. The task is performed under the supervision of an operator equipped with a remote control device. The tracked vehicle is mounted on caterpillar tracks and is fitted with a means for locking on to the structural component. There is also a communication link between the AGV and the crane in order to coordinate the positioning process via the operator. The use of these devices means that people are removed from a hazardous process, although an operator is retained to supervise and make remotely controlled adjustments.

3.3.2 Floor Laying

This process uses mobile robots to position prefabricated floor modules. The modules are likely to be made of lightweight steel frame cages containing all the services that the floor is expected to carry. A hard surface incorporating access-panels covers the top of the modules providing a base for wood or carpet finishes. The robot selects the appropriate module, locks on to it and pushes it to the respective position within the floor grid. The operator is left to make the final connections. This form of floor construction eliminates the concurrent installation of several services and finishes thereby reducing the number of on-site operatives working within the same area. It reduces overall construction time, improves quality control and has the potential to save cost. Operations would be directed by the MPCP.

3.3.3 Partition Placing

Partition walls are divided into panels which are manipulated and located by mobile robots. The panels carry services and fixings, and are prefinished or manufactured in such a way that allows for a range of different decorations to be applied. The robot is fed with the panels, erecting them at their respective location within the building as directed by the MPCP. The fixings and connections between services are executed afterwards by operatives in a similar fashion to that adopted for floor laying. An advantage of this approach is that partition walls constructed from panels enable changes in space requirements to be accommodated more easily than is possible with traditional brick/block walls. Major concerns with this process are the logistic problems involved in handling the panels and in protecting the finishes. Also, subsequent changes in the location of the panels may involve modification to services conveyed in the ceilings or floors.

3.3.4 Cladding Erection

This process incorporates a mobile robot for erecting the cladding and a server robot for feeding the mobile with cladding panels. The erection robot positions the panels on the outside of the building whilst operating from inside. The cladding panels, which are designed according to the developer's/building owner's specifications, have standard jointing systems. The process consists of unloading a set of cladding panels on to the working floor using a crane which operates with the assistance of the server robot. This robot feeds the cladding erection robot with panels at its current working position. The erection robot places and holds the panels on to the building structure whilst an operative completes the fixings. This system has the advantage of enabling the task to be performed from inside the building rather than from outside, thus eliminating the need for scaffolding.

3.4 System Integration

Several areas need careful consideration before the processes described above could be successfully implemented on a building project; for example, management of the site, training of the workforce, robot set-up costs, maintenance, power supplies and the scheduling of construction processes.

4. CONCLUSIONS

In general, there are two trends in the application of robotics within the construction industry. The first tries to automate traditional construction processes in an attempt to replicate the performance of operatives; the second deals with the rethinking of building design with automation in mind. Modular system building plus automation constitute the latter approach. The use of prefabricated and mass-produced components, supported by a family of dedicated, simple robots would narrow the gap between what the industry can deliver at present and the higher level of expectation that exists amongst building owners and users.

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