ADOPTION OF SPECIAL MATERIALS FOR THE DEVELOPMENT OF CONSTRUCTION AUTOMATION

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ABSTRACT

The development of construction technologies, which will be more readily adoptable to automation and robotization will, to a large extent, determine the success of this new field. The present paper discusses new developments in inorganic (cementitious) and polymeric materials, that could be adopted, with some modifications, for advancing new construction methods, based on simple, single stage operations. Such materials and methods could be particularly efficient in various finishing works, that are usually labor intensive and complex. Some areas where research could be fruitful are identified, and several developments of simple construction methods based on new and improved materials are described.

1. Introduction

The development of construction technologies which will be more readily adoptable to automation and robotization will, to a large extent, determine the success of this new field. In many instances, advancement in new construction methods is dependent on the availability or development of materials of special properties. One may classify the materials needed for such purposes into two: Materials for structural and non-structural "bulky" components (columns, beams, panels, blocks, etc.) and materials for "non-bulky" application, mainly finishing and connections (adhesives, rendering systems, coatings, flooring, etc.).

accelerated, depending on the needs and requirements associated with the production technology and the surrounding climate.

The cured and hardened cementitious mix can be strong and durable, especially when the cementing material is portland cement. Yet, these materials are quite brittle and prone to drying shrinkage effects, making them sensitive to cracking and debonding. Thus, when applied for coating and flooring, additional means are required to enhance their serviceability: special modification of the material itself or modification of the construction process by means such as joints.

In this section of the paper, some recent developments in the modifications of cementitious materials will be critically reviewed, from the point of view of their future potential to be applied for the development of construction methods that could be easily adopted to robotization and automation on site.

2.1. Self levelling mixes

The development of self levelling mixes can be extremely useful for simplifying the flooring finish operation, using a simple process which involves only one step, i.e. pouring of the mix. Self levelling mixes with inorganic cementitious matrix is not a new concept. The development, in recent years, of new and powerful admixtures to improve workability (2) has enhanced the applicability of such materials. Yet, their use is met with some problems. Mixes based on portland cement tend to segregate to a small extent, and although the surface is levelled and smooth, the upper layer may be somewhat weak, making it less durable and less resistant to abrasion. As a result, such mixes can serve as a substrate over which some additional thin coating of surfacing material must be applied. A common alternative is to use a matrix of different binder, such as gypsum and oxy-chloride cements (Sorel cement) which perform much better in the fresh mix, with very little segregation and bleeding. The surface obtained can be thus stronger and of improved abrasion resistance. Special formulations have been developed for this purpose. For example, many of the gypsum self levelling mixes are based on α-gypsum with various admixtures, which can be made as a flowing mix at a relatively low water/gypsum ratio, leading to a high strength material. However, these materials have limited durability in wet environment, which restricts their application.

It is self evident that in the case of robotization it will be extremely important to apply "bulky" building components of low unit weight and sufficiently high strength, i.e. high strength to weight ratio, in order to enable relatively small, possibly mechanized robots, to place "bulky" components at a reasonably large range. Such components could be made of foamed materials or sandwich type elements with a strong, durable skin and a lightweight inner core. Although the application of lightweight-foamed components is quite common in the construction industry, they are not yet ideally suitable for robotization and automatization. Foamed plastics can be produced in the desired weight, strength and accuracy, but their use is met with difficulty because of drawbacks, such as fire resistance and sensitivity to volume changes due to temperature floctuations. Inorganic cellular materials like foamed autoclaved calcium silicates provide a strong and durable material, but at present their unit weight may not be sufficiently low, and it is difficult to produce components with the accuracy and profiles required for automation on site. Also, the finishing operations over such inorganic (cementitious) cellular materials is sometimes difficult because of the high level of capillary absorption of the background.

A second important field is the operations involving connections between components and their finishing. These can be complex operations which are usually labor intensive. It is in this field where the applications of new materials, classified previously as "non-bulky", can be extremely rewarding, since it will enable to simplify the operations to a level that could be carried out by robots or other means of automation, without requiring the development of complex equipment. Such equipment is needed when the operation is complicated and requires the application of different tools. The use of self levelling material for flooring may serve as a good illustration of this point. The development of such a material, which when poured down will not only level by itself (to provide a straight and smooth surface), but will also yield a wear resistant surface, can extremely simplify this type of finishing work. In terms of equipment, it will require a machine or robot which will need to do only one operation - pumping of a fluid mix. Levelling, screeding, troweling and polishing, and special treatment of the surface will be avoided. At present, there are various types of cementitious and polymeric formulations for self levelling mixes, but they still require some additional finishing work, especially for providing tough and wear resistant surface.

The object of the present paper is to review some recent developments in construction materials that may serve to simplify various building operations and make them more readily adaptable to automation and robotization. The main emphasis will be given to the second field of applications, i.e. "non-bulky" materials for finishing and bonding between components. This review is not intended to be a comprehensive one, and it will deal only with material systems which we believe to be potentially suitable for early use in conjunction with robotization and automation of construction. It should be pointed out that, although many of these materials are already being applied in the conventional construction industry, they will have to be modified and improved in order to meet more stringent requirements. This paper will include also some results of a preliminary study where such materials are being applied to simplify construction of block-walls, which is a complex, labor intensive operation, and lend it applicable to robotization. The topics discussed here are related to modifications in various building technologies, that are needed for efficient operation of robots, as discussed by Warszawski and Navon (1).

2. Inorganic Cements

Inorganic cements (portland cement, gypsum, etc.) have been popular building materials for quite a long time, one of the reasons being the simple technologies that can be applied to produce building components with these cements. When mixed with water and aggregates, a fluid mix is generated that can be easily placed and shaped. In recent years many types of mineral and chemical admixtures have been developed and adopted, to modify the properties of the fresh mix, and make it compatible with various production technologies, ranging from simple placing and compaction to more complex operations such as spraying and slip forming. The setting and hardening of the fluid mix is the result of a chemical reaction between the cement and water. The rates of this reaction can be controlled by various chemical admixtures, either slowed down or

Recent developments in supplementary cementitious materials may prove to be useful in developing new formulations for self levelling mixes, free of the limitations discussed previously. Special reference should be made to microsilica (also known as condensed silica fume) which is an extremely fine pozzolanic material consisting of spherical particles of 0.1µm diameter and characterized by a high content of amorphous silica (>85%). When combined with portland cement and superplasticizer, an extremely fluid mix can be obtained, that is at the same time quite dense, as a result of efficient packing of the fine microsilica particles (0.1µm diameter) between the bigger cement grains (10µm diameter). As a result of this dense packing and the high reactivity of the microsilica, an extremely dense material can be obtained in a short time period, with compressive strength values in the range of 100 to 200 MPa. The presence of the fine microsilica particles eliminates segregation and bleeding. This characteristic, combined with the fluidity of the mix and its high strength (due to the low effective water/cement ratio) make it a potentially suitable material for self levelling mix that will also yield a durable and abrasion resistant surface.

The development of such a mix will reduce the sensitivity to cracking, due to the reduced shrinkage of this material. Yet, because of its brittleness, the hardened mix may be still prone to some cracking and joints may still be required. To overcome this limitation, to enable the production of a tough and durable flooring surface without joints, or with a small number of joints, the hardened material should be made more ductile. This could be achieved by incorporation of polymer latex into the mix. A more comprehensive discussion of the effect of such polymers will be given in section 2.2. Thus it seems that the development of a mix with a three component matrix of portland cement - microsilica-polymer latex may prove useful for generating a simple, single stage flooring operation, which will require no additional finishing work such as surface treatment and joint preparation.

2.2. Polymer Modified Cements

Many of the limitations of portland cements for various finishing operations or bonding purposes, are associated with the brittleness of this material and its tendency to shrink, both effects leading to sensitivity to cracking and debonding from the substrate. Such effects are commonly observed in rendering systems. The incorporation of polymer latex in the portland cement system can provide a useful means for developing portland cement based systems free of these limitations. Such systems have been used for various repair and resurfacing purposes. Their application can be extended to provide coating systems that will be multipurpose: to generate bond between various elements, as well as to serve as external coating to provide visual effects and protection of the structure, i.e. preventing ingress of moisture. For example, a simple dry brick building system could be developed, in which brick or blocks are placed together to the full height of the element, and the polymer modified portland cement mix is sprayed over the whole brick wall. This mix, which is characterized by high strength and ductility, may provide a strong enough surface bonding, holding together the whole brick wall. In such a system, only two relatively simple operations will be required: placing of blocks and spraying of mortar. There would be no need for bonding separately the individual bricks.

The polymer latex is a fluid dispersion containing about 50% by weight of tiny polymer particles (0.1μm in diameter) and 50% water. The polymer is "film forming", i.e. when the water dries out, the polymer particles approach each other and coalesce into a strong and ductile film. Polymer latexes compatible with portland cement are added to the fresh mortar or concrete mix which is then handled (mixing, casting and curing) as a normal mix. On curing, the cement hardens, and the polymer particles coalesce into a film which forms a tri-dimensional reinforcing network within the mix, bridging between the cement matrix and the aggregates, and between the mortar or concrete mix and the substrate on which it was applied. The presence of this ductile film, and its bonding effect, result in increase in tensile (flexural) strength, ductility, abrasion resistance and bond strength to the substrate (2)(3). Also, the polymer film in the matrix leads to low permeability and improved durability. The reduced permeability is associated also with small rates of water evaporation during drying. This characteristic, combined with the improved ductility, result in reduced tendency to cracking. Therefore, this material is suitable for making rendering coats which might be applied as a single layer, that can provide all the functions of the coating layer. This is to be contrasted with conventional rendering which is applied in 2 or 3 layers, with each providing a different function. It should be indicated that a properly formulated polymer modified cement may not require water curing, since the polymer seals the surface and prevents the evaporation of water needed for cement hydration. Thus, the application of such materials can provide a surface coating of improved performance (less cracking, improved bond and impermeability) and at the same time will simplify the application process which will require only a single layer without any additional curing. This single layer could be readily applied by spraying which is a simple operation to be carried out by a robot.

The use of polymer modified cementitious systems may be also of an advantage for developing self levelling mixes, as discussed in section 2.1. The improved ductility, durability and abrasion resistance is extremely important for providing a strong and crack free surface with a mix that could be applied in a single step of pouring without any need for additional operations such as surface treatment, curing and joint preparation.

2.3. Fiber Reinforced Cements

Fibers are added to cement to improve the tensile strength and ductility of the brittle cementitious matrix. For most applications, like coating and bonding mixes, it is the ductility which requires special attention, since enhancement of this property will reduce the tendency to crack and will thus indirectly lead to improved bonding and impermeability. Improvement in strength is of lesser importance. Therefore, for this kind of applications, it will be sufficient to use low-modulus polymeric fibers, like polypropylene, which improve ductility and have only a marginal effect on strength. Higher modulus fibers (steel and glass) will enhance strength as well as ductility (4).

The reinforcement with fibers can be particularly useful for rendering system which can provide structural bonding as well as rendering coat of improved impermeability. This material has served as a basis for the development of dry block construction system, in which the application of the reinforced rendering system induces the structural integrity of the block wall. This is again an example of a simple building process involving two operations: Placing blocks and applying a rendering coat. This system was developed in the USA using cement reinforced with glass fibers. In view of the cost of glass fibers and their limited durability, there is a need to evaluate such systems using the more durable and less expensive polypropylene fibers. As indicated previously, the low modulus of the polypropylene may not necessarily be a disadvantage, since it is mainly the improved ductility which is needed in such applications. The presence of fibers may be also beneficial to the properties of the fresh mix, making it more thixotropic, i.e. reducing its tendency to sag after being sprayed on the wall.

The use of fiber reinforcement may also be useful for developing various thin sheet cladding elements that are lightweight, but at the same time strong and ductile. The improved ductility enables applying fixing procedures such as nailing or mechanical fastening which are readily automated. The presence of fibers prevents propagation of cracks at the impact point, and from this point of view, the fiber reinforced cement performs like a wooden panel.

3. Polymeric Materials

There seems to be no doubt that polymeric materials will play a major role in the development of building automation processes and that the use of this young family of materials will increase with the expanding of automation and robotization in the construction industry.

Polymers are organic materials composed of macromolecules ("chains") of very high molecular weights. The macromolecules are a result of polymerization of very low molecular weight materials known as monomers. The monomers are usually flowable materials - gases or liquids, whereas the polymers are solids; in the process of polymerization low-viscosity materials transfer into solids or very high viscosity materials.

The suitability of the polymeric materials for the automation processes in the building and construction area has a few major reasons:

a) The family of polymers is very versatile and the variety of materials available is large covering almost any need and desired property. Thus, for example, one can find polymers which are soft and flexible and others which are hard and tough.

Furthermore, the polymers can easily be compounded or modified physically to produce materials of the desired properties. A good example of such a modification is the formation of lightweight foams which are produced by incorporating blowing agents in the raw polymer. Such foams can be produced in the factory as prefabricated materials or on the spot at the construction site.

b) There are many polymeric materials that are liquids or low viscosity flowable materials prior to their application and solidify to produce a continuous solid after application. It is unnecessary to stress and emphasize the importance of such systems in the construction processes to be used in automation or robotization.

The solidifying procedure can be either of chemical or physical character. The chemically solidfying systems are usually prepolymeric or even monomeric materials which, by their nature, are low-viscosity flowable materials. After the application a polymerization-curing process takes place forming a high-molecular weight solid material. The best known example for such systems is the epoxy resin (which is a versatile family by itself) in which a prepolymer liquid resin is mixed with a hardener and cures after a while to form a crosslinked polymeric material. Another system of the chemical curing type, which has gained popularity lately, is the acrylic resin (PMMA) which is applied as a low viscous prepolymer solution and is polymerized after application to produce a hard and durable polymeric material.

The physical solidification methods makes use of a system which already contains completely polymerized materials in the form of an emulsion or solution. Such a system can be highly fluid (e.g. paint) or paste-like (e.g. sealant) depending on the required end use. After application of the flowable materials and the drying of the emulsion or solution, the polymer forms a continuous solid.

c) The required properties of the fluid material, prior to application, and the solid material after the curing, can be controlled relatively easy. This refers mainly to the viscosity of liquid on one hand, and the mechanical and solid state properties of the material on the other.

The range of viscosities of the applied materials can be varied and chosen from very low viscosity, highly flowable materials to paste-like materials which flow only under pressure; this, even within one family of resins like the epoxids.

A variety of solid state properties can be achieved, as well, based on the requirements, whether within one family of polymers (e.g. soft or hard polyester) or by choosing and modifying a proper resin, to achieve a soft sealant or a hard coat of a floor.

d) Another important feature is the low density of the polymeric materials in comparison to the more conventional building materials like concrete, stone or steel. The density of most bulk polymers is about 1000 kg/m^3, whereas that of concrete is about 2400 kg/m^3 and steel - 7800 kg/m^3. As mentioned already, some of the polymeric materials can be expanded to form foams of densities as low as 15 kg/m^3.

The low weight is of prime significance in the area of automation and robotization.

The features mentioned make polymeric materials particularly suitable to be used in construction automation in the following ways:

a) constructional adhesives and cements.
b) sealants.
c) self-levelling floors.
d) coatings and rendering materials.

It is important to mention also the availability of polymeric products like prefabricated continuous plastic sheets for roofing or flooring, which are very suitable for automation processes of laying by robots. Yet, this subject is beyond the scope of this paper and will not be dealt with here.

3.1. Polymeric constructional adhesives and cements

Many polymers have properties that make them excellent adhesives. An adhesive should fulfill two main requirements: one - it has to spread and thoroughly wet the surfaces of the adherent, and the second - it has to solidify after application and withstand the strain and stress applied to the bonded subjects.

As mentioned already, many polymers are available as pre-polymeric resins or other fluid material which can solidify after use. There is no question that the most suitable adhesives are the epoxides. These materials are characterized by their excellent adhesibility to various materials. They are easily applied, spread well and cure chemically without losing any solvent or releasing water, thus avoiding shrinkage of the adhesive upon solidification. The chemical curing forms a crosslinked metwork which has excellent mechanical properties and durability.

The large variety of epoxides and their properties, both in the pre-cured state (i.e. low or high viscosity) and post-cured state (i.e. flexible or rigid solids) made them very popular and attractive adhesives for construction purposes.

The bonding by adhesives can actually replace mechanical bonding or welding without lowering, and sometimes even improving, the strength of the bond. The adhesive bonding can be used for connecting steel to steel, steel to concrete, and concrete to concrete.

The low viscosity of the adhesive and the ease of application make this method of bonding very applicable in automation and robotization processes. A special example for the use of adhesives in automated technologies, which is being tested in our laboratories, deals with the injection of adhesive cements in dry wall building system, as described in chapter 4. The epoxy and PMMA polymer tested are injected in between layed blocks and spread through the entire wall, forming finally, the bonding material between the blocks.

3.2. Sealants

Polymeric sealants are commonly used in the building and construction processes for the sealing of joints: both insulation and control joints. It is anticipated that the use of sealants will further increase with the introduction of automation processes. These processes, which will most likely facilitate the use of large prefabricated parts of the building, will also create the need for constructional and non-constructional joining of the building parts. The polymeric sealers will be the main materials to give the answer in the case of the non-constructional joints, whereas the adhesives will play a major role in the constructional bonding.

The large variety of polymeric materials for joint sealing, their flexibility, ductility and resilience enable this family of materials to give the proper answer almost for any width of joint - from a few millimeters to a few centimeters.

The polymeric sealants are usually high viscosity materials that can flow under pressure into the joints. After the application they usually cure physically or chemically to form the proper sealing material of the desired properties.

The most common sealants are polysulfides, butyl and neophrene elastomers, flexible polyureathes, silicones, and solvent and emulsion (latex) based acrylic polymers.

3.3. Self-leveling floors

The subject of self-leveling floors as an important technique in the automation technologies, was discussed in section 2.1, dealing with inorganic cements for this purpose.

Polymeric materials, whether pure or compounded with inorganic additives, may have the proper solution to this automated building process, as they have the required properties for it:

- low viscosity and good flowability.
- short curing times of solidification.
- low shrinkage during solidification.
- excellent abrasion properties.

As mentioned already, many polymeric materials exist in their pre-polymerized form as very low viscous fluids. These systems - epoxies, PMMA and polyester resins - can be easily spread over large areas and self-level without any troweling or mechanical spreading. Yet, they cure relatively fast, to produce a continuous tough and hard solid substrate. The curing time can be largely controlled by the proper compounding of the resin. The curing process transferring the liquid pre-polymer to a solid polymeric material is a chemical process without the release of any solvent or other material, and the entire liquid system turns into a solid. The solidification is thus free of any shrinkage that might cause cracking of the floor. It is therefore possible to cast floors over very large areas.

A major requirement of flooring materials is good abrasion resistance. Polymeric materials are usually characterized by excellent macromolecules are very difficult to be pulled out of the surface by abrasion. Crosslinking of the molecules, as is often the case, improves this property even further.

It is important to indicate that organic polymers have relatively high coefficient of thermal expansion in comparison to concrete or metals. This has to be taken into account when designing a continuous floor cast from a polymer mixture.

3.4. Coatings and wall rendering materials

Wall rendering with layers of conventional plaster or stucco is a tedious, labour and time consuming process. Automation technologies may save much of the time and manual work needed, yet it requires the introduction and use of new materials that can be applied on the wall in a single step and continuous process. It is important that such rendering material is flowable enough to be sprayed on the structure, but stable enough not to flow off a perpendicular wall or from a ceiling, even if it is applied as a thick layer of a few milimeters.

The main advantage of polymeric materials, in this respect, is their Thixotropy: low viscosity when exposed to high sheer-stress (e.g. during pressure spraying) and high viscosity when exposed to low sheer-stress (e.g. when adhered to the wall). Materials having this property can be easily sprayed, but will not flow off the wall by their own weight thus forming a homogeneous and continuous layer.

Wall rendering of this kind and type are mainly based on polymeric binders compounded with mineral fillers, pigments, reinforcing glass or organic fibers, and others.

Appropriate polymeric materials for this purpose could be based on acrylic latices, polyester solutions and more.

The intention of this chapter was to point to the great potential of the polymeric materials in the development of automation processes and robotization technologies in building and construction, and not to be a comprehensive state of the art review of this broad subject.

Thus, only a few examples of possible uses were pointed out. Obviously there are many other areas where the suitability of polymeric materials in automation processes can be exhibited: e.g. continuous spraying of foamed insulation, to mention one.

One cannot ignore or overlook a major disadvantage of these materials: their relative high price. Nevertheless, we believe that the saving in manpower and labour achieved by the introduction of automation and robotization is a proper economical compensation for the higher materials' cost, and will result both in improved quality and lower costs.

4. Dry Wall Building Systems

Brick and block construction method is relatively complex and labor intensive. Yet, there is interest in preserving this type of traditional construction (which is basically a flexible modular system), and at the same time make it adoptable to automation. Dry wall building systems seem to be one of the more attractive approaches to deal with this problem. Such systems, based on laying of blocks and applying a strong and ductile rendering coat were discussed previously. At present, we are engaged in a research project aimed at studying more thoroughly the problems associated with such systems and the evaluation of altnerative approaches to the bonding between the blocks and the connection with the structural frame around them.

One of the bonding systems being evaluated is laying of blocks produced with special profiles at their edges, that provide a continuous "closed" channel between neighbouring blocks. After placing of the blocks, a 2-dimensional network of the channel is obtained, surrounding all the blocks. Pouring or injection of a fluid mix at one entry point can fill all the spaces around the blocks, and when it hardens it will bond them all together into a stable structure.

Regardless of the type of bonding method used, there are special materials problems that have to be addressed and solved. The blocks to be used in such systems will always be lightweight, with the most attractive approach being the application of cellular inorganic materials (gypsum, cement, autoclaved calcium silicates). Such materials are characterized by a high absorption capacity, which results in difficulties in application of rendering coats or bonding materials that tend to be absorbed into the background. This problem is being addressed by two alternative solutions: (a) modifying the surface of the block by treatment with various polymers to impregnate the pores, and (b) modifying the rendering or bonding mix to make it more cohesive and less inclined to be adsorbed. Modification with various polymers, including the polymer latexes described in section 2.2 seems to be a viable solution.

5. Summary and Conclusions

In the present paper, the properties of some new polymeric and inorganic cementitious materials were reviewed, emphasizing their potential to be used for simplifying building operations, to make them adoptable to robotization and automation. The discussion dealt only with those materials which, in our view, can be more readily applied in this new field. Areas where research and development could yield fruitful results were pointed out. It should be born in mind that in order to make use of the full potential of robotization and automation, there is a need to deal not only with the hardware and software of the "construction machines", but also with the technology and the required building materials. Interdisciplinary work is required and it could yield fruitful results. In the present paper some areas, where new technologies and materials could be of benefit, were identified.

It might be interesting to note the similarities between the requirements from construction technologies applicable to unskilled labor on the one hand, and to sophisticated machines, like robots, on the other: In both cases, they would preferably be based on a simple, one stage operation. Self levelling mixes for flooring is an excellent example. Thus, construction processes and materials that will be developed with the view of being applied by sophisticated machines, may also find use in areas where skilled labor is unavailable or expensive. This may be the case in do-it-yourself jobs or in developing countries.

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PLANNING FOR ROBOTICS ON CONSTRUCTION PROJECTS

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ABSTRACT

The use of robots in industry is now commonplace particularly for assembly processes in the manufacturing industries. The construction industry is similar in many ways to manufacturing in that a high proportion of the workload consists of what are basically assembly operations. However, it is constrained by the environment, the fact that design and production are divorced and construction is not standardised. These are probably the major reasons why little or no serious consideration has been given to the use of robotics. This paper considers initially the potential for the use of robots in the construction industry based on a feasibility study undertaken in collaboration with construction companies, plant hirers and manufacturers. It can be concluded from this study that due to its conservative nature any major initiatives for robot development must, in the main, come from outside the industry e.g. plant manufacturers.

The second part of the paper examines potential applications at three levels. First, the development of autonomous or semi-autonomous devices which can navigate in the relatively unstructured environment of the construction site. These are general problems of information gathering, processing and planning capability. Secondly, the design of devices in respect of their physical functions; namely, locomotion on site and manipulations for handling, processes and assembly. Thirdly the higher level problems of the design of the building or civil engineering structure to facilitate the use of robotic devices. The potential areas of construction automation will be examined with respect to these three problem levels.

INTRODUCTION

For the purpose of this Paper the term advanced robotics covers robot devices which are independently mobile and are able to "understand" their environment so as to be able to make decisions about how to proceed with the task required. This distinguishes them from existing industrial robots which operate from a fixed location in a largely repetitive pre-set manner, and are able to re-programme themselves to meet changes in their working conditions.

The construction industry is labour intensive and tends to place its emphasis on maximising output per employee. It is subject to a large number of external influences that must be taken into account and involve trade-offs, e.g. between the need for high productivity and low costs, and the requirement to spend substantial sums in turning out a high value product. There is often an over-emphasis on current operations as opposed to forecasting future trends in terms of efficiency and competition.

The industry in the main fails to take advantage of advances in technology or to see them as a means of achieving a more efficient and profitable construction industry in the future. There is also an assumption in the industry that years of training is necessary in order to become competent in a technology and that technology based decisions must be left to Scientists and Engineers. However, to understand the technology, a manager needs to know only four things; the cost of the technology, what it will do, what it requires and the reliability of the answers to these three questions.

As the world's economy becomes more integrated there will clearly be greater competition for contracts. In addition the technology is continually changing with significant advances in such techniques as computer-aided design, robotics and computerised machine systems. Equally important, the consumer is demanding increasingly varied products, thus forcing construction companies to adopt new techniques, produce buildings in shorter production runs with a greater degree of customisation.

These changes present the construction industry with a considerable challenge. It is perhaps not surprising given the low status accorded to them that the industry is experiencing difficulty in responding to this challenge. In the past change has inspired relatively minor switches in production styles in individual companies e.g. a new piece of plant, a new computer system for financial planning or a new planning technique. These changes have been reactive and not pro-active or planned.

Spectacular advances have been made in the robotisation of production over the past decade, particularly in the manufacturing industries, to date these advances have not progressed into the construction industry, certainly not to any great extent. However, the Japanese have carried out a considerable amount of research and development in this field.

In the UK at the present point in time the construction industry is lagging behind in many respects e.g. working conditions, status and, accordingly, it has not proved attractive to young people. There is therefore a lack of skilled labour a situation balanced to an extent by the introduction of alternative forms of construction that are less demanding in terms of trade skills.

In general construction work is carried out under poor working conditions often in situations that are injurious to health, e.g. high or low temperatures, dust, poisonous gas, compressed air, water pressure etc. Not only does this make the industry unattractive, but it also results in a level of industrial accidents well above those experienced in other industries.

Warsawski[1] links these factors with "the dispersion of construction activities over many sites, distinctive nature of each product, changing work location within the project" as major obstacles to "the robotisation of the construction process".

He goes on to suggest that "Despite these conditions many building construction activities can be robotised at the present stage of technology with promising economic results given an appropriate design of the robotic equipment and a suitable organisation of the construction tasks".

Furthermore, although productivity in the manufacturing industries has increased substantially during the past decade through automation and robotisation, productivity in the construction industry has stagnated. This situation linked with the factors highlighted above points to the fact that there is considerable potential for the introduction of robotics. What is lacking is an identifiable demand from the Industry itself. A feasibility study was undertaken in the UK by the authors in collaboration with construction companies, plant hirers and manufacturers. The main objectives of the study were as follows:

Objectives:

(i) to determine the current usage of robotics on construction sites;

(ii) to identify those site operations most suited to the use of robotics;

(iii) to consider the implications of promoting the use of robotics to:

- (a) increase productivity and reduce costs
- (b) eliminate manual tasks particularly those involving heavy physical strain and risk of injury
- (c) maintain production where labour is scarce or too expensive
- (d) reduce material wastage

Although a number of positive responses to the study were received, the general reaction displayed a high level of apathy and scepticism.

PLANNING AND CONTROL

If robotisation is to be a practical proposition, it is important to establish precepts and guidelines for the planning and control of particular and specialised operations and develop a special philosophy of control for the use of robotics. There are two aspects to this:

(i) the problem of site lay-out and the planning of movement and activity ares

(ii) controlling the dynamic situation as construction proceeds.

<u>Site Layout</u>

No two sites present the same problems and a lay-out suitable for one site may be quite unsuitable for another. The main planning features are movement, storage, activities, access and control. When envisaging the use of robots it is essential to consider operations in particular phases, e.g. where a clear change of work or control is envisaged. It is important to show the movement or action density in the various activity flows, for example excavation may require the use of very heavy equipment in addition to robots. A buffer area may be necessary. Concrete work for the substructure may require special systems depending on the method adopted e.g. the use of concrete pumps or monorails will determine the need for centralised site control. It may be useful to give each phase a particular weighting devised, perhaps, on the complexity of movement, i.e. vertical and horizontal. Clearly site layout is not static but dynamic and will change physically during each part of the project duration. It is important to determine the activity or area most in need of control during each identified phase.

It will be important on all sites to determine a central focus or series of central focuses about which all other activities will revolve. In other words the "centre of gravity" of each particular structure is determined around this focal point all other operations in that area can be co-ordinated geometrically for the site to produce a common centre of gravity which becomes a focus for all operations. In particular the point of access will influence the focal point. It must be remembered once again that this will not be static but will change with the dynamic nature of the activities involved.

It is likely that in any particular phase one of the activities e.g. concrete work may hold co-ordinative priority and should, therefore, be considered first. This may take place in a number of phases and therefore its position must be relative to all types of movement i.e. it may be necessary for it to operate within reach of casting and placing areas, and within the crane sweep of other phases giving vertical and horizontal movement, or alternatively, it may also need to relate to vertical movement of, say, hoists in other phases as the building progresses.

It will be necessary once the positions have been decided to give directional orientation relative to the access. A typical system could relate to specific interior finishes and connecting activities which could be associated with both the storage area and the actual placement point. This can be planned as a peripheral activity in a number of phases. Structural steelwork, for instance, will be influenced by the position of the access road for easier handling by robot in the early stages of the project. Later, however, if a crane is available it could be moved to the far side of the fabrication area if this were found to be advantageous. Once ground work and substructure has been completed the second phase introduces the third dimension of height requiring attention to aerial movement and here robots may be used in conjunction with a crane on hoists and the site layout may now require readjustment. As the work progresses internal partitions and finishes will come on phase, control now assumes a wider span with a much more dynamic approach to communication between activities and possibly a more intensive use of robots.

Horizontal and Vertical Access

Once a structure has become partially erected access to the points of activity must be provided.

If robots are to be used careful planning and control of working accesses and material placing will be an essential feature.

It is common practice to use the permanent doorways and windows for gaining access to the interior structure. This is often more a matter of expediency rather that appropriateness. Consideration must therefore be given to the provision of temporary access points to be used during construction allowing robots to penetrate deep into the structure carrying pallets or containers for depositing materials at a point of use. Access points must be closely controlled to prevent the blocking of entrances and exits with waste materials etc. and ensure uninterrupted movement. One possible solution is the use of preformed access tunnel units that could be positioned at strategic points in the external envelope of the building.

Vertical access to buildings is achieved largely using cranes and hoists. However, when a roof or floor slab is in place, the chance of lowering goods into position is reduced and a less effective from of horizontal access must be used. By careful planning materials and components can be positioned before the covering unit is placed in position. Openings left in roofs and floors create difficulties in waterproofing the building. This problem can be overcome by fitting sliding covers to give protection. Vertical access, other than a lift shaft, will always present design problems due to the possible effect on the strength of the structural elements. However, with careful planning it is possible to leave out complete sections of floors and flat roofs without creating design difficulties.

Horizontal and Vertical Movement

Having gained access, the internal movement of robots and the distribution of material and components to the various points of use must be planned and controlled. The problems of illumination associated with humans does not of course apply to the use of robots.

Key factors for consideration at the early planning stages are movement, storage areas and activity areas. Movement within the structure should be designed to ensure correct positioning of components, materials and plant with the routes to be used within the structure clearly defined and controlled. In relation to robots, three distinct situations can be identified viz. robot stationary, materials stationary (fitting, welding etc) robot turning, materials moving (bricklaying, door fixing etc) robot moving, materials stationary (duct work, painting). Horizontal movement of robots must take priority over goods and the path to a storage area must be clear and as direct as possible. Obstacles must not be placed on the planned route.

Traditionally, vertical movement is confined to ladders placed in floor openings. These are both difficult to negotiate and dangerous to use. The use of robots will require a complete rethink in terms of this type of movement. The use of ramps may present a possible solution. They are however, costly to construct, a factor that must be judged against other potential benefits i.e. cost benefit analysis.

Communication

The use of robots will require a completely new approach to problems of communication. Central points must be identified including the lines of physical communication between activity and storage areas. Access points and routes for components, materials must be defined and potential conflicts eliminated. Contact distances between robots, operatives, plant and materials must be kept to an absolute minimum. Some of the problems may be overcome by the use of radio link systems for instance with intermediate communication points along the communication lines.

THE ROLE OF ROBOTIC AUTOMATION

The construction industry context for the development and introduction of robotics has been introduced and it is clear that there are difficult technical and organisational problems to be overcome in the change to increasing automation on the construction site. The potential reduction of direct manual operations can contribute to improvements in quality, inspection and consistency. It is these factors rather than the removal of labour intensive operations which are central to the evaluation of potential robotic applications. This is not to say that robotic automation does not offer the possibility of reducing labour costs but rather that there are other major benefits which will accrue if automation is considered as a radical rethinking and restructuring of construction operations.

The wide ranging research and development in the area of robotics can clearly make a contribution to many construction operations on site. However, this contribution must improve the quality, consistency and ultimately reduce costs and increase efficiency. Generally the introduction of robotic automation in manufacturing industry has focussed on a whole spectrum of benefits. Initially these centred around the reduction of cost and saving of labour, although they are now increasingly focussed on improvements in quality and the potential for integrating automatic inspection within a complete system. The robotisation of specific tasks has reduced importance as the robot is called upon to play an integrated part in the automated system. The isolated areas of robotic automation appear to be of little benefit to automated and flexible production. There are a number of reasons, including the fact that overall flexibility is not necessarily enhanced by such islands of automation and without attention to the integration with other production processes the robotic automation may give limited advantages with respect to labour saving, cost reduction or quality improvement.

The general lesson to be learned from the introduction of robotics in manufacturing industry is that robot devices are to be considered as an integral part of the automation, performing critical functions in manipulating objects, tools and inspection equipment which require dexterity and programmability. Robotics as such can make a substantial contribution to the implementation of flexible automation, but the systems in which they are incorporated have a significant impact on the manufacturing strategy and the range of manufactured product.

The extensive and various benefits which can accrue from introducing flexible automation have only started to be explored. As indicated they are not confined to the manufacturing operation alone, but extend through the production planning, product design and the development of corporate strategy.

These effects of flexible automation and robotics will not be mirrored exactly in the different environment of the construction site. However, the argument here is that the wider issues of flexible automation should be considered from the outset in introducing robotics to the construction site. The use of robotics will not only have an influence on the methods and processes of construction but also on the design of the building and the planning and organisation of the construction process. The influence on the building design is complex in that not only will the available automatic construction operations impose restrictions on final design but also that the process of realising the design on site will require that the building is designed with greater attention to the sequence of construction operations to allow access and support for robotic devices.

AUTONOMOUS DEVICES

The complexity of the environment on the construction site implies that the introduction of robotic automation requires the ability for intelligent action in response to a variable and evolving environment for the construction tasks. It is this theme which has formed much of the focus of attention in this area. The construction and application of software tools in task planning and the control of autonomous action from the fields of artificial intelligence and computer science has been viewed as the necessary level at which robotics can make an application to the construction industry. This is indeed the case when the current design practices and methods of site organisation and planning construction are considered. It is advocating that these practices and methods should change radically in the introduction of robotic construction processes.

There seems little doubt that the construction site will remain a complex environment when compared to the imposed order and well-structured world of the manufacturing plant. However, there is always a single planned and well-structured reference in any construction site; namely the building as it is erected. The complexity and imposed order implied by this structure increases as the building assumes its final form giving rise at the later stages to a potentially highly structured environment. The main problems here which demand significant attention are centred around the ability to use this structure in the guidance, control and support for robotic automation.

BUILDING DESIGN DESCRIPTION

There are considerable difficulties in making available the knowledge of the current building form at any stage in construction to the robot device, although the information is potentially available provided the design of the building either contains explicit references to the construction sequence, or this information can be inferred from the final design description. We argue that a generative method should be applied to the synthesis of the building design which can be used to reflect the stages of construction towards the final design. This is dealt with later in the paper.

It is precisely this aspect dealing with the knowledge of the developing building form which can impose order on the robot environment and provide the means by which the extremes of autonomous action in complex and unpredictable environments with the associated time and expense of considerable information processing, data base management, inference and planning can be avoided. We argue that with adequate preparation in the structure and organisation of the sequences of construction operations, the application of robotic devices will provide substantial benefits, including reduction in cost, improvements in quality, methods to initiate inspection at critical stages in construction and generally the organisation of the work. However, we stress that this requires the appropriate tools for the design and description of the building which are based on generative and rule based means to preparation of the design and its subsequent realisation as a sequence of construction activities on site.

TASK SPECIFIC ROBOTS

The application of research in autonomous machines and vehicles lies at one end of a spectrum of robotics research which will have application to construction. This spectrum includes the development of machines and flexible robot devices suitable for the tasks encountered in construction. These are the task specific machines corresponding to the islands of automation in the manufacturing system. They may be used in a teleoperator mode to allow remote operation. Indeed it should be remarked at this stage that many of the current advances in construction plant could well take this form in the near future.

The advantages of remote operation are increased safety and awareness of surrounding operations. Further, the removal of direct manual control introduces the possibility of intelligent software to offer advice and guidance on the conduction of the particular operation. Inspection routines can be insisted upon and monitoring of correct procedures can be made easier. There are many examples of robot type devices or manipulators which can either perform a single task repeatedly or which act under the individual and direct control of an operator. These devices can be further enhanced for semi autonomous or autonomous operation in which the detailed control is handled by intelligent software to make choices between alternative course of action. The rules for planning actions may be incorporated in an expert system. However, as mentioned above this requires knowledge both of the particular operations and of the environment in which the operation is required to be executed. It is considered that without an appropriate design description of the building construction, such autonomous action is not feasible. Thus for the extension of remote controlled and semi autonomous operation knowledge about the task and the context in which it is executed must be available or capable of being inferred from the building design description.

ROBOT DEVELOPMENT

In addition to the extensions of existing construction machinery for remote control and autonomous operation there is another area of robotic research which has considerable application to construction. This corresponds to the development of new mechanical and electronic devices integrated under the title of 'Mechatronics'. These developments have largely been led by Japanese research in the creation of new mechanical and electrical devices together with the means for their computer control. Much current work in advanced robotics relating to robot gripping technology and new robot actuation schemes is conducted under this heading. They offer the possibility of new devices looking for applications. The construction site with its wide range of manipulation and assembly tasks could provide a field for the application of these devices. Generally, any such application demands that a number of elements are composed into a single machine capable of moving to a required position on the site, manipulating building components, performing process operations and assembling the building components.

Examples include machines for climbing the frames or faces of a building, special purpose devices for fixing panels, automatic floor laying and levelling machines. Again, it is argued that such machines make special demands on the form of the building design for their successful implementation on site. The satisfaction of these demands places considerable pressure to reassess and develop design descriptions of the building form.

In this paper it is emphasised that the development and evolution of machines to aid and accomplish construction operations is vital to continued improvements in efficiency and quality on the construction site. However, these devices do not stand in isolation from the building design itself. In general they receive support for motion and locomotion from the existing building and they will work within the devloping and changing context of the building as construction proceeds. At the other end of the automation spectrum, the autonomous and intelligent devices will also require the partially completed building as a framework for support as well as design information on the nature of the environment in which they are to work.

It appears to the authors that the pursuit of general purpose autonomous devices on the construction site may be out of place at the moment, in that the present environment is probably too complex and ill structured to lend itself to exploitation of all but the most flexible machines. The flexibility required is a compound of the manipulative and locomotive flexibility together with intelligent software for meeting complex goals in an ill structured environment. There appear to be limits to the usefulness of extensive flexibility since the potential penalties of speed and cost accumulate.

The authors contend that a combination of elements will lead to successful robot automation of building operations. New mechanical and electrical devices capable of autonomous action on well defined tasks in closely supervised and planned environments can be integrated with the building structure. The building process can be planned for use of robotic devices and the building form as a sequence of construction estimates designed for the purpose of using robots.

THE BUILDING DESCRIPTION

The construction industry context for introducing robotics has been explored above. There is some interest from the major contractors in the development of special purpose remote controlled and semi autonomous machinery. This interest is mainly focussed on the solution of isolated problems. The central research problems in the area remain those of understanding the nature of the building activities, the context in which they occur (including the means of material and component transport but more crucially the environment of the partially completed building) and the means to describe the building design in such a way as to integrate robotic execution of its assembly.

There is no doubt that such a perspective is looking ahead many years. It does not contribute immediately to the problems of reducing cost, improving quality and increasing efficiency. For many of the engineers concerned with the detailed planning and operation of construction sites such a research viewpoint will not be significant. However it identifies the context in which problems will arise in robotic automation and suggests the design issues to be considered in making the most effective use of the manipulative, locomotive and autonomous capabilities of robots.

The automation of manipulation, handling and locomotion requires a particular point of view in understanding the building and the processes of construction. The activities appropriate for robotic automation fall into three categories, corresponding to those used in the manufacturing applications of robotics. The robot device may be used to transfer or handle components, assemble these components or to manipulate tools. Each of these takes place in the spatial context of the partially completed building, the development of automatic handling and transfer to the site of assembly requires that information be readily available on possible paths to the site of assembly, the partially completed building acts as the context, the constraints and possibly the framework for this transfer. A robotic transfer device acting within a building must maintain an up-to-date record of the current state of the building assembly. Further, the planning of an automated building should present the building as a sequence of evolving geometric entities, be able to plan the routes for automatic transfer and evaluate different methods, routes and orders of building assembly. In general the problem of automation is not in the final design of the building but in the 'designs' of the building at various stages of its construction. To this end it is essential to emphasise the close and strong connection between the development of CAD in architecture and construction and the implementation of robotic automation. It is necessary to develop a CAD system capable of considering the building in a generative sense. The generated geometry is constructed by the robotic automation and importantly the automation itself forms part of the developing building geometry. In the final building much of this subsidiary framework will be removed although the requirements for continuous inspection and monitoring of large structures made possible by the use of autonomous inspection robots may lead to such frameworks forming an integral part of the final building form.

GENERATIVE BUILDING DESCRIPTION

The CAD description of a building construction thus becomes generative, corresponding to the stages of construction and the assembly operations in placing components. We argue that the appropriate descriptions for creating building designs which may be used for implementing robotic assembly of buildings should be based on shape rule applications to generate the building form. These generative spatial rules may be expressed in the form of shape grammars[4]. The essential power of such rule based approaches to design descriptions lies in two areas. First, the generative procedures can be used to reflect the on site construction operations and second that they allow the generation of many possible alternative designs within the rule base.

The details of the shape grammar formalism and its potential application to building descriptions appropriate for the robotic automation of construction has been the subject of a previous paper[5]. This enterprise is still in its early stages and requires a radical reorientation of the kinds of CAD system required which incorporate rules for the generation of form 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. The development of such a CAD system is thus aimed primarily at enabling the designer to set up a world in which the processes of conception, synthesis and evaluation of the design for robotic construction can take place. The characteristics of these 'worlds of design' will differ between application areas but it has been argued[6] that in the field of architectural design shape generation is the major and defining thrust, rather than the function led approach to descriptions which may be appropriate in other areas of engineering design[7].

CONCLUSION

This paper has reviewed the areas in which robotic automation may be used in construction and has detailed some of the activities and perceptions of the construction companies in their approach to this area of technology. The main argument of the paper lies in the proposal that generative rule based systems for the creation of building designs is as crucial a step in this process as the development of the robotic devices themselves. Autonomous robotic machines require appropriate design descriptions of the building to make available the necessary information about the developing building geometry on the construction site.

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