Automation and Robotics in Building Construction

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Summary

The development in the field of construction is being predominantly characterized by increasing shortage of skilled labour. This shortage will have to be compensated for by an increase in the level of prefabrication to be achieved in the manufacture of pre-cast concrete, wooden, steel frame and brick wall building elements. As an example I describe here the increasing market demand for pre-cast concrete roof, ceiling elements and pre-cast concrete wall elements to pre-cast concrete columns and beams as well as advanced precut systems for wooden elements, steel element factories and automated brick wall facilties and on site systems of robotics and automation.

1. Automation and Robotics in Prefabrication

On the basis of the development of the European market for that product, the intention to invest in that product can be regarded as farsighted in order to stay competitive and promising for future economic success. The application is available for the most advanced CAD and CAM technologies currently available to the manufacture of double wall elements, massive walls, ceiling and roof elements, column and beam elements. As there has never been any plant automated to this degree, development tasks will continue to account for a large per-centage of the work to be done [1].

In traditional manufacturing in high wage countries the share of labour cost increases faster due to low mechanization rate. Applying mechanized manufacturing methods allows labour cost share reduction up to 30% by increasing mechanization rate. According to the mechanization ratio a minimum lot size of about 30 elements is required. Most gains can be achieved by automated manufacturing using robots, CNC machines and FMS in order to further reduce the significance of labour costs. Traditionally automated factories required a minimum lot size of 1000 or even 10.000 pieces to guaranty ROI. Through the use of FMS (Flexible manufacturing systems, robots, off line programming methods, hybrid control systems etc.) it became possible to run a one of a kind production efficiently. Most present day CADCAM factories reach their ROI point after 3-5 years. They can run 1-3 shifts, producing 1500 to 2000 m^2 (16,145.88 ft^2 to 21,527.84 ft^2) of floor-wall panels per shift [2].

Another substantial advantage in favour of the pre-cast con-crete elements consists in the job efficieny of the workforce. As the building site personnel is to a far lesser extent concerned with somewhat more complicated tasks, such as, for example, moulding, insertion of reinforcement steel, etc. than is normally the case with regular construction workers, job efficiency at the plant level reaches an optimum that cannot possibly be arrived at on a building site. Costs of transportation are approximately the same both for the prefabricated elements and for corresponding quantities of site-mixed concrete [3].

An increasingly competitve construction market asks for new flexible production as well. Due to the notion of robotic handling devices any shutters can be freely positioned. Recent trends in flexible manufacturing technologies offer solutions for PC production placed on a platform using magnetos. This development allows to cast free shaped and designed panels in concrete and produce one of a kind elements very efficiently as required. Similiar technologies are available for prefabricated masonry systems, which can be classified in two categories [4]:

- horizontal masonry element production (Winklmann System)
- vertical masonry element production (SÜBA, Anliker, Weiss System)

What we have to do next with the CAD data is to use them for rapid precast concrete production by robotics as strategic advantage for improuving quality and staying competitive during chaotic market conditions. Similar technologies are available for wooden structures using precut-CADCAM-production systems or for autoclaved lightweight concrete which can becarved by threedimensional milling center.

2. On site Robotics.

Considerable benefits of field robotics will be realized, as soon as we link it up to any kind of CAD system in order to implement computer integrated construction. Here I describe the progress and obstacles faced by the first generation of construction automation and robotics which have been developed and tested during the 80's mostly in Japan and the greatly increased potential that will be evident in automated building systems, which are tested in the 90's and will be furthermore implemented in the first half of the 21st century.

The challenges of developing robots for construction jobsite are much greater than those of most factories. First the products of construction are much more complex and ill structured.Second, in contrast to the repetitive products that flow down production lines, the design of the construction product and the process to build it are individually adapted in each case. While the manufacturing process is highly repetitive once production starts, that in construction is always changing. The physical environment of construction is often much more hostile to machines as well as people, so machine design must be stirdy and robust accounting for extremes of weather, dust and unexpected forces [6].

Given the difficult and complex environment of construction, it is remarkable that robots and automated machines are already performing routine tasks on some jobsites. The first construction robots have either been derived by adding sensors and computer-based controls to existing construction equipment (e. g., to control the cutting edges or screeds on various types of earthmoving and paving equipment, robotic tower crane etc.), by adapting the comparatively rigid factory-type robots to construction (e. g., for spraying fireproofing material or painting), or by developing hybrids of the two (e. g., robot arms mounted on tunnel machines) [7, 8]. While the sophistication of their mechanisms and sensors has often been quite high, these robots have had only the most basic forms of on board "intelligence."

Most of the construction robots developed to date are stand-alone devices designed to perform narrowly defined tasks without the need to communicate or cooperate with other machines. However, coordinated teams of robots quite commonly perform sequential operations on factory assembly lines, and there are some formal communication mechanisms linking them together and similar technology also moves to construction in the dozen or more automated building construction systems or the EU project „ROCCO“ which stands for „robotic assembly system for computer integrated construction“ and has been scientifically developped by the author between 1992 and 1996. Since then the ROCCO prototype has been successfully marketed by the LISSMAC corporation for commissioning building components in the building material sector and will be further implemented in the prefabrication of masonry elements [9].

2.1 ROCCO: RObotic Assembly System for Computer Integrated COnstruction

The system deals mainly with the construction oriented modification of existing technologies and with closing the gaps between them through intelligent interfaces and IT-based tools, in order to provide the necessary flexibility for one of a kind building production, robust design and user friendly programming. To achieve the requirements, the above mentioned basic strategies for automated construction are applied: the information integration, the production of the prefabricated masonry walls and the commissioning of the construction materials. The main emphasis lies on the creation of automated system, which enables the complete and continuous automation and the integration of computer based construction systems, without restricting the freedom of the design of the architects. With that system one can build in a shorter time with fewer personnel more and better buildings.

Within the ROCCO project a robot system had been developed for the assembly of masonry not only in the factory but also on-site. The robot system with a reach of 6 m and a load capacity of 1000 kg can consist of a vehicle , the actual robot or manipulator and a gripping and assembly tool, if required. In the framework of the working preparation, the necessary data for the pre-fabrication of the costumized blocks and for the robot programming are generated.

Based on a CAD representation of the building, first the walls are divided into the single blocks automatically by a software tool. The next step contains the planning of the construction site layout, i. e. calculation of the optimal working points of the mobile robot systems, the space for the pallets, the configuration of the blocks on the pallets and the sequences of the block's assembly. With the then available information the customized blocks for realizing individual wall dimensions can be produced, cutted and palletized on stationary plants. The last step of the working preparation is the generation of the robot programs.

2.1.1 The integrated information management

The chosen approach bases on the idea of Computer Integrated Manufacturing (CIM), which is already successfully implemented in other industries and which shows there its efficiency. The idea is a continuous information flow from the architectural design to the automated execution of construction process on-site and in consideration of the construction elements. This procedure, called Computer Integrated Construction (CIC), makes it possible to automatically process all once collected data without loosing the data consistency. This enables all participants to stay as flexible as necessary during short-term changes with as low error rates as possible.

2.1.2 ROCCO's information flow

To integrate the complete construction process in an IT-framework, as many as possible process steps should be based on electronical data processing. For the masonry we describe following a complete integrated information chain from the architect's design to the robotized execution of the tasks on-site, where all tasks are based on electronical data processing. This concept is IT backbone of the ROCCO project and represents the state of the art in European computer integrated construction systems.

The plans in the architectural offices are created with CAD-systems. On these base the production of standard and non-standard blocks in the pre-fabrication with the computer based production scheduling and numerically controlled production. This enables again the use of programmable assembly tools and systems on the construction site. The corresponding information flow is shown on the picture below.

To use the architectural design data for production planning and programming in the prefabrication and on the construction site, it is necessary to process and to extend the data.

After processing the incoming CAD-data, all necessary geometrical information as the positions and the dimensions of the blocks on the pallets and in the wall as well as the positions of the pallets and the robot system are available. Together with the assembly sequence, all data is onhand to be able to generate the control programs for the pre-fabrication production and cutting machines as well as for the on-site assembly robot system.

2.1.6 The robotic pre-fabrication of building components

The operation in the pre-fabrication plant can be divided into two basic procedures. First the production of standard wall elements in different formats. The production is not specific for a certain order. No custumization is necessary. Therefore the only necessary information for the production scheduling is the number of blocks and their main format. So non specific software tool is necessary to process the data before using it for the production of standard wall elements.

Another situation is in the production of the non-standard wall elements as the second main procedure in the pre-fabrication. To get an efficient production of these elements, it is necessary to have a continuos information flow :

- The cutting sequence optimization, which minimizes the waste number of cuts considering different boundary conditions: The features of the used cutting equipment as the number of saw-blades or the thickness of the saw-blades, the features of the palletizing equipment as the ability to palletize randomly or the maximum number of the simultaneously available pallets. The software uses similar algorithms as the palletizing software in the one-line field.
- The cutting program generation, which processes the geometrical information of the blocks into the motion information of the respective NC-controlled cutting axises.
- The assembly sequencing program generation, which generates the motion programs for the assembly. The generator has to consider not only the necessary final positions on the wall element. Depending on the design of the gripper, it is also necessary to consider the logistics of the blocks in order to determinate the approach direction to avoid collisions during wall prefabrication.

The fully automated and computer-integrated pre-fabrication of the elements represent an important prerequisite for a smooth assembly process on the construction-site.

3. Automated Building Construction Systems

A major step toward an integrated system of robots is now being undertaken by some of the mid-size to large contractors who promote the development of systems that will substantially automate the construction of mid-to-high-rise buildings, and about a dozen of these systems are being deployed. Basically, they consist of a jack-up frame or push up jacks on which or below which a variety of robots for materials handling (e. g., cranes, hoists); fabrication (welding, cutting, finishing); and inspection are installed. The frame will have an all-weather enclosure to enable work to continue around the clock, at any season of the year [10]. This framework will initially be positioned at the first of a series of repetitive floors to be built, and the robots will do about 30-70% of the work to construct that floor. Next, the whole frame jacks itself up to the next level, and builds another floor. The idea is somewhat like a slip-form for constructing a concrete structure, except that a whole building, not just a concrete structure, is "extruded" from the system. This process continues until the building is done, then the automated components are removed, leaving the frame in place to become the structure for the top floor of the building.

The systems are in part motivated by an expected shortage of skilled labor in Japan, but over time will have economic and quality advantages similar to those of an automated factory. About 90% of present labor requirements will be replaced by automation. Those workers who remain will probably be highly skilled technicians who can program and maintain the robots. The systems provide for substantial integration of structural, mechanical, electrical and finishing operations that are used in the construction of a building. There are also obvious interfaces to and interactions with design. In this way they represent the computer-integrated-construction (CIC) systems of non manufacturing industries [11].

Impressive as such automated building systems will be, there remain many challenges facing the advancement of construction automation and the development of more capable construction robots. Perhaps the most difficult is that of developing the intelligent software to integrate future machines into the complex environment where they will work.

Before considering what should go into the core of construction robot software, it is important to think about some bounds on this software. Relative to the intelligence to support the successful execution of construction tasks and to the intelligence and human dimensions of a typical construction worker, we are still looking at a most rudimentary kind of "intelligence" to form the core of a construction robot's software.

In general, what is needed is some way of modelling within robot agents some feeling of their environment, such as key characteristics of objects and other agents, in ways useful for reasoning. We have to reduce the knowledge that needs to be encoded in machine systems a priori by enabling them to tap the vast knowledge sources in their environment when needed. This is extensibility, which some might call a simple form of machine learning. Robot societies or groups should be able to assemble knowledge and enlist other agents needed to perform a task and respond dynamically to change. Robot reasoning and control software should deal with unexpected obstacles, road conditions, failure of a machine-positioning system, damaged material, improper tools, or imprecise instructions.

4. Service Robotics

4.1 Interior finishing robots

In order to use robots for future service systems we collected experience in the technology of AGV (automatic guided vehicles) concerning kinematics, navigation guidance control and design of a control of conditions. The kinematics of vehicles known for automatic movement on construction sites. Such a kinematics was developed by my center for technology transfer, but further alternatives should be worked out. Autonomous vehicles navigation is a very complex problem and therefore extremely difficult to be realized in the ill-defined construction site environment. In the midterm hybrid systems offer a higher potential for construction site application. One example is the interior finishing robot presented here [12].

4.2 Semiautonomous glass roof device

Another promising application of CAD data into service systems and robotics is the field of half -respectively full-automatical maintenance of façades under different surface-conditions [13]:

Fields of examination are:

- Height reaching devices
- Ergonomic investigation of facade maintenance
- Cleaning and maintenance methods of different facade surfaces
- Prerequisites for the use of automatic or telemanipulated facade maintenance devices
- Economics , serviceability
- Testing and control by simulation

Aim of the researching-efforts is the development of a semi-automatical façade-service implement for the maintenance and diagnostics of skycraper- façades and other areas of building which are accessible from outside. The implement shall be programmable as well as navigateable by remote-control, and it shall be flexible concerning the tasks (cleaning, diagnostics by camera, maintenance, ...) and the use (suitability for buildings already existing). A robotic subsystem for maitenance robots is the vertical locomotion capability as presented by the RoSy II climbing robot [14]. By using a platform device for handling intelligent or robotic tools such as the surface preparation system „Beaver“ robotic technology could be potentially marketed in the huge renovation and repair market, which represents about one quarter of the total German construction market [15].

5. TR /CSCW: TeleRobotics/Computer Supported Cooperative Work

Global AEC projects require a multi-designer and multi-construction-machine system which has a realizeability capacity. It also provides a cooperative creation environment from design activity to prototype construction, which is indispensable for product development and the predictive simulation of complex construction projects. The requirements, the necessary functions and the implementation of a “cooperative tele-designing and tele-construction system“ which is distributed on a computer network [16]. The necessary technologies which have been implemented for a cooperative tele-designing and tele-construction system using the Internet are as follows: [1] visual information display, such as predictive display of geometrical information to compensate for time delay and real-time construction assembly display using multi-axis force information, [2] predictive auditory information presentation using a physical model of block assembly and an information transformation technique, [3] predictive force information presentation, [4] tactile presentation of the state joining as high frequency vibration, and so on. The software system was implemented as a multi-construction -machine system. Necessary agents and their functions are discussed based on the system, as implemented and tested [16].

6. Intelligent Production Systems

Examples to be considered here include artificial intelligence, CADCAM, robotics, and fully integrated construction project planning, design, management and production control systems.

Already there have been many efforts to apply the evolving computer science software technologies loosely called "artificial intelligence" (AI) to construction. So far, most construction investigators have focused on techniques called "expert systems" and "knowledge-based systems," although some have recently been moving into a new area called "neural networks."

The main reason for trying to apply such methods to construction is to deal with the qualitative and prototypic types of problems that are so prevalent in those parts of the industry where the construction is mostly executed on-site. The most valuable career asset for a construction professional is not mathematical or scientific skill of the type taught in engineering schools, but rather it is a methodology to use the not yet existing human experience to solve new problems. Another objective of construction is to capture the knowledge of experienced architects and engineers in computer programs so that other construction engineers and managers can access it and apply it, perhaps even after the experts who provided the knowledge are no longer available due to personnel fluctuations. Such programs also provide a means to integrate and validate the knowledge and experience of many experts, and thus provide a means for accumulating and improving a body of knowledge over time. A good example of this sort of knowledge are the 800 precut systems currently in action in Japan, where the craftmanship of the famous „daikusan“ or carpenter, who could carf all the traditional japanese joinery, has been programmed and generated CADCAM production of traditional joinery at affordable cost. Furthermore this type of knowledge could be very helpful considering the long product life cycle of the built environment and retrieving it for future recycling.

Implicit in this type of computer application is the need to deal with uncertainty in the information needed to design, build and operate a building. For example, design starts with only general conceptual knowledge of what a project will look like when it is completed. Yet as early design decisions evolve into commitments for configurations, materials and systems, they can adversely affect constructions costs and schedules, and compromise the efficiency and effectiveness of facility operation during the whole life cycle of the built environment.

AI techniques can capture knowledge of construction methods and management making this available at the design stage during which about 70% of the construction costs are determined. For example, if a designer has a choice of configurations for a wooden structure, an expert system could provide advice as to which would be most economical to build.

A promising area for future applications of AI technology is in planning, monitoring and controlling the construction process and costs in real time. Up to date we controll construction costs statistically instead of adjusting the process in real time. Already there have been some good attempts to build construction planners of various types, and other applications have been made to analyzing construction contracts, preparing construction cost estimates, and select construction methods. Other important applications for intelligent agents will be in helping people to coordinate the vast amount of documentation that is generated in a large construction project, and to assist in negotiating the long and complex permitting procedures that are now required for most projects. Probably the most interesting applications will occur when AI techniques supplement or replace the procedural programming that is now used for one of a kind prefabrication, automated machinery and construction robots.

7. Beyond factory and site automation

The factory automation already reached a sufficient level of automation, but as for the on site environment, which is ill defined, unstructured and shape-changing, there may not be accurate correspondence of an agent's knowledge about the environment to its real state at any time. So we have to prefabricate as much as possible in the structured environment of factories and only realize the final assembly on-site. In future construction field environments, intelligent machines, like their human counterparts, will thus need to gather knowledge to plan and control autonomous tasks. Not only the robots, but most of the intelligent agents will need a unifying core of intelligent software and a framework for defining and communicating knowledge about designs and field operations in a way that can effectively be utilized for their production tasks.

Conclusion

It is clear that A+R technologies will continue to advance quickly in other industries. But what we need is how effectively the construction industry will adapt to and exploit this technology for its own advancement. If we do so successfully then we can cope with the structural changes that are now taking place in the construction industry. If robotics and automation will not only be used for academic presentations but also for controlling the adequate construction processes, then we can stay competitive during the chaotic market conditions that lie ahead of us.

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