CONSTRUCTION ROBOTICS

Prof. Dr.-Ing./Univ.Tokio Thomas Bock
President of IAARC
Chair for Building Realization and -informatics
TU Munich, Arcisstrasse 21, D 80333 Germany
www.bri.ar.tum.de

1. Introduction

Robots were originally introduced in the production of industrialized building components and modular housing. Later mobile robots were developed for special on-site construction tasks. Automated construction sites use robotics for logistics and assembly. Recently humanoid construction robots have been developed and tested.

2. Overview

In the 1970s, many companies producing building materials on an industrial basis were founded by companies not otherwise engaged in construction. Ideas from automobile manufacturing, ship building and the chemicals industry were adopted by the construction industry. The 1980s saw the introduction of robots on building sites where they carried out specialized tasks such as spraying, smoothing concrete, distributing materials, fitting equipment to ceilings, assembling form-work, installing facades, painting and many more. In 1988 I published "ROD"(Robot Oriented Design) in Japanese after having witnessed the development of 50 construction robots. ROD concept aims at facilitating the application of robotic technology to construction by creating a robot oriented construction and design periphery. In the 1990s, integrated systems for high-rise building were developed. These automated construction sites used robots for logistics and assembly till 2004. Since 2002 humanoid robots have also been used for various applications on site, such as fitting interior walls, helping to carry slabs and driving forklift trucks and diggers. Recently we have developed service robots for daily life. [1]

3 Robotic Precast Concrete Panel Production

Figure 1: Flexible CADCAM gantry type production unit for PC floor, wall and roof elements using two robotic end-effectors for reinforcement positioning: Figure 2*: Robotic concrete distributor*

The robotic precast concrete panel factory designed in 1990 uses a multipurpose unit which allows flexible production of unique concrete floor, wall and roof panels. First the robotic cleaning unit cleans the production table and then sets regular spacers. Next the multi functional gantry type robotic unit with two vertical arms places magnetos on the steel production table according to the CAD design data. In a third step the robotic unit attaches shutters on top of the magnetos and then places horizontal, vertical and triangular reinforcement bars according to structural engineering data. In a fifth step a CADCAM controlled concrete distributor spreads the right amount of concrete while controlled by a CAD layout plan considering installation, window or door openings. The whole system is quite flexible and can create any layout or be run by rush order or optimal panel layout on the steel production pallet.

4 Prefabricated Masonry Walls

Figure3: Robotic cutting and sequencing of bricks Figure 4*: Robotic spacing and positioning of bricks for customized masonry wall prefabrication*

Since the typical German customer prefers masonry homes, we developed various robotic prefabrication systems for wall and floor panels with bricks. Basically we implemented two versions: one version where the walls had been erected vertically. Here the advantage was that we did not need to tilt the panel during factory production process. There were systems where a robotic gripper assembled a brick at a time and in Figure 4 a whole layer of bricks had been positioned either vertically or layer by layer or horizontally on a steel table similar to the concrete panel production system described above.

In between the layers another end-effector placed horizontal reinforcement bars and a robotic mortar pump spread mortar on each layer. Then due to logistic requirement we placed vertical reinforcement bars in at least two locations where the in-house gantry crane and the on-site tower crane could grasp the panels. The advantage of the horizontal masonry wall/floor panel production system was that not only brick or limestone elements but also concrete panels could be produced. Such a flexible device costs about 25% more but allows the employer to respond better to market demand fluctuations.

5 Robotic Wooden Panel Production

Figure 5: Robotic vacuum gripper for customized wooden panel production Figure 6*: overview of a factory with robotic nailing and gluing bridges for wooden panel production.*

6 Robotic Production of Three-Dimensional Steel Units

The Toyota Motor Corporation is known for its automobiles. However, it also has a factory for prefabricated houses in which it has successfully transferred manufacturing technology from the automobile sector to the construction industry. Toyota Homes produces from 4.5 to 7 houses per worker per year. A Toyota house is assembled from room cells in up to 12 different sizes in four to six hours. In the factory, a room cell is prefabricated every 2.5 minutes.

Customers can put together their dream home from over 350,000 single parts. Computer-aided design and computer-aided manufacturing systems produce approximately 2,000 components from around 25,000 parts, which in turn make up approximately 300 functional modules. Despite such a huge variety of parts, essentially no manufacturing defects arise.

To make sure that customers do not become confused by the huge amount of choice, they can use virtual reality to walk through their dream home and can change anything they do not like before they sign the contract. If they approve of the simulation of the house and agree with the price and the financing terms, the CAD/CAM system starts to manufacture the components and room cells, which leaves hardly any waste. The quality of the robot-aided manufacture at Toyota Homes is so high that the company gives a warranty for their prefabricated houses of ten to twenty years. They are high-value products, manufactured with industrial expertise.

In a country where wages are high, a high-investment business will only thrive if it can operate continuously with help from the marketing department. Like the Toyota Motor Corporation, Toyota Homes is managed on a marketing-oriented basis. Marketing controls the robotized production systems at Toyota Homes in the same way as the Andon and Kanban systems at Toyota Motors. Customer orientation comes first, which builds up a good reputation with satisfied customers. This service is rewarded with increasing sales of prefabricated houses in Japan where the building industry is otherwise in decline.

Figure 7: Quality End Control of a box unit with bathroom from a flexible manufacturing system Figure 8*: Onsite assembly of a box unit house*

Sekisui Heims factories produce 25,000 houses every year. A network of 30 distributors serves Japan and takes a care of sales and installation. The factory is the most advanced of its kind producing more than 100 units each day equipped with a flexible welding robot that can weld 9 types of units. Machine tool change accounts for about 5 minutes while the welding process only requires 2.5 minutes. The modules measure about 2.5m x 2.8m. Main procedures are cold folding of the edge frame members, including the connections- assembly of the edge frame by multi point welding robot infill manufacture.

The Sekisui suppliers work on a four-day cycle, planning one day for processing the order and preparation, two days for manufacture and one day for shipping. To fabricate a module it takes one day in the factory and 15 men working on it. On site operation requires one day for 10 men to pour the foundations in place with a metal framework; installing the modules for a 120 m^2 house takes between 4.5 and 6.0 hours according to traffic and road conditions, requires a 20 ton crane and 10 people and finishing lasts 10 days with 3 people. Sales are direct.

The Misawa Homes organization is a franchising type business including 1 Inuyama factory for Palc box units, 170 distributors, 1,200 licensed installers and 90 maintenance and improvement centers. The majority of wood panels are prestressed skin type boards.

7 On site Construction Robots

Early on-site construction automation and robotics were implemented in the civil engineering sector due to repetitive working tasks such as road construction, tower and bridge building, dam construction, LNG tank construction (Shimizu), nuclear power plant construction (Shimizu) and tunneling(Shimizu).

8 Mobile Site Robots

Big Japanese construction companies have been researching and developing robotized construction processes since the beginning of the 1980s. Initially, individual robots and remote-controlled manipulators were developed for specific processes on building sites. This included robots for delivering concrete, handling concrete, applying fireproofing to steel constructions, handling and positioning large components and, as a final example, facade robots for plastering and painting. Over 400 different prototypes were developed and tested on building sites. They all had in common that they were intended for use on

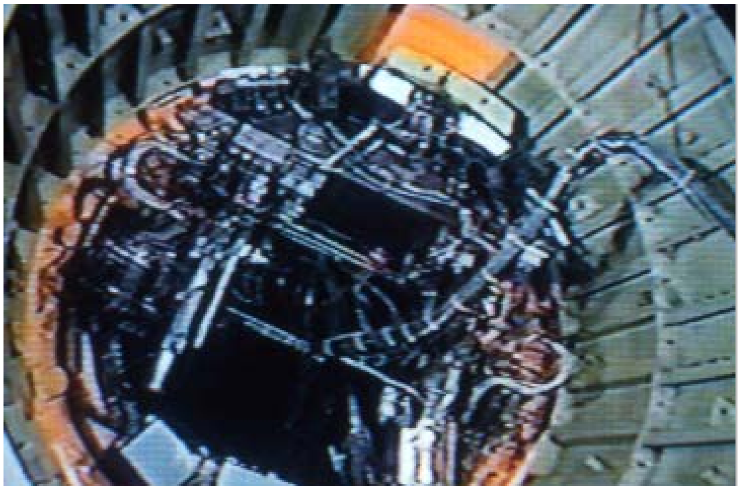

Figure9: Robotic concrete roller for tunnel construction Figure 10*: Robotic tunnel segment assembly unit*

specifically defined tasks under building site conditions and were not supposed to have an adverse affect on the work carried out by the construction workers. It became clear that only a few robots were economic to use under these conditions. The restrictions on the workers, the safety regulations and the unforeseeable and unplannable events that affect building sites strictly limited the use of individual robots in parallel with normal work. There are only a few such robots currently in economical use or offered for sale on the market. Examples are the concrete smoothing robots from Takenaka, Shimizu, Kajima and Tokimec. This development revealed that it is difficult and, in particular, not economical to transfer production conditions from the factory floor to the building site. This might seem to be a mundane and predictable result, but it must be acknowledged that these developments were only seen as a first step on the way to automating construction processes and that profitability was not the primary objective.

There are two other crucial results of significance to the future of the Japanese construction industry. The first is the knowledge and skills acquired in the area of automation and robotics, and the preparation of workers for innovation in the construction industry. The second is the groundwork for the real objective - to automate the final assembly of a building on a building site under factory-like conditions and in bringing to bear the laws familiar from serial production.

9 Mobile Finishing / Refurbishing Robots

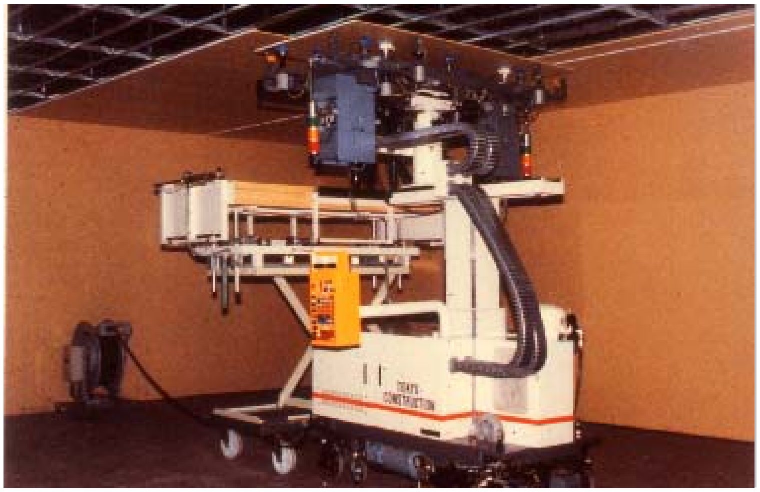

Figure 11: Mobile ceiling drilling robot, Figure 12*: An interior finishing robot for mounting of suspended ceilings*

During the last decade the German construction market shifted from new construction towards rehabilitation and modernization of existing building stock. During new construction there is a high degree of mechanization, but in modernization we face a high degree of labor cost and less mechanization. Therefore in the 1990s we developed various robots for interior work in order to increase productivity of building stock modernization.

10 Mobile Servicing Robot Systems

In Japan the first facade and roof robots were developed and put into operation at the beginning of the 1980s. It should be noted that these devices were almost without exception developed by the technical departments of large building companies or by their construction machinery suppliers and not by service providers or cleaning equipment manufacturers. This was due to the narrowly defined area of application of the equipment

Figure 13: Construction material distribution robot Figure 14*: Façade diagnotics robot*

which, as a rule, was used only on one large building erected by the company in question. There are many varied applications. Initially there were bulky, rail-guided robots such as the exterior wall-painting robot from TAISEI, which was developed to apply paint to the 100,000 m^2 facade on the 220 meter high Shinjuku Center Building in Tokyo.

11 Automated High-Rise Construction Sites

The first prototypes for automated high-rise construction sites were put into operation in 1990 and 1991 by Shimizu after five years in development and a financial outlay of almost 16 million euros. Since then, 20 automated high-rise sites have been operated by different companies (Taisei, Takenaka, Kajima, Maeda, Kumagai).

An automated high-rise construction site is understood as the semi- and fully automated storage, transport and assembly equipment and/or robots used to erect a building almost completely automatically. It is the attempt to improve the sequencing of construction processes and construction site management by using real-time computerized control systems. This includes an unbroken flow of information from planning and designing the building through programming the robots with this data to using computers to control and monitor building operations on site.

Figure 15: Automated construction site SMART(Shimizu) seen from above Figure 16*: Two of 22 robotic trolleys for transporting and positioning of beams, columns, floor panels, building services units and facades*

After the foundations have been laid, the production equipment, on which the steel construction has been installed with assembly and transport robots, is covered completely with a roof of plastic film. Depending on the system, this takes from three to six weeks. Then the robots go into action. Two steel and ten concrete plants supply parts in ten-minute cycles on a just-in-time basis. This approach to supplying is not necessarily part of the system, but is due more to the lack of space around building sites in large Japanese cities. The prefabricated parts are checked and then placed in specific depots at the foot of the building or in the building itself to be available to the robots. This is where the automated construction process actually starts. Up to 22 robots equipped with automatic crane winches deliver the pillars, supports, floor, ceiling, wall and other elements to the floor of the steel skeleton under construction. They are also mainly positioned and fixed into place automatically. The steel pillars and supports are joined together by welding robots after they have been positioned. The position and quality of the welding seams are monitored with lasers.

Once a story has been finished, the whole support structure which rests on four columns is pushed upwards by 12 hydraulic presses to the next story. Three 132 ton presses in each pillar are required to achieve this in 1.5 hours. Fully extended, the support structure is 25 meters high; retracted it measures 4.5 meters. Once everything has been moved up, work starts on the next story. By fitting out the topmost story of the high-rise as the roof at the beginning of the building process, the site is closed off in all directions, considerably reducing the effect of the weather and any damage it might cause.

This system reduces labor requirements by around 30%. Future projects are expected to achieve a labor saving of around 50%. The building consists of a remarkably high proportion of prefabricated parts. Once the foundations have been laid, the remaining construction procedure can be described as a matter of configuring transport and geometry. All the elements are prefabricated; only some of the fitting, joint insulation and other minor works need to be carried out by hand. Problems with the construction arise less from the timing of deliveries of materials or from the choice of processes and/or machines but more from the need for accurate planning, from programming the robots or from the just-in-time supply of parts.

12 Robot Oriented Design

ROD is a method / strategy to reengineer conventional construction processes. During an analysis of 50 construction robots in the eighties I realized that robotic systems were prone to failure, defects and malfunctions, if they were just doing the same job as human workers did. Therefore I developed a strategy in order to reengineer the construction process and redesign construction details and building components in such a way that it facilitates the implementation of construction robots. I termed this strategy “Robot Oriented Design or ROD”. Between 1988 and 2004 originally automated building construction sites used this approach efficiently. Nowadays even conventional construction sites which use prefabricated components apply this concept successfully.;

13 Humanoid construction robots

Humanoid robots for construction work have been developed and tested for six years. The robots can carry a joinery bench together with a construction worker, fit an interior wall, and drive forklifts or diggers. They can move over gradients of around five degrees and compensate for up to two centimeters on uneven surfaces. They can right themselves when they fall over.

Figure 17 shows a humanoid robot riding an excavator*

When carrying a component with a human, they use an adaptive and flexible arm system. An image processing system with a mobile portable control system has been developed to allow location detection. When it moves over uneven surfaces, a force sensor in the sole of the foot and a balance sensor in the body register the difference and the gradient allowing the robotic control system to adapt the sole of the foot to the surface.

14 Ergonomic construction robotics

A UK-led construction consortium, ManuBuild, representing ten European countries, has secured 10 million Euros of funding from the European Union for a four year research program, with a key focus on the supply of housing. It is the largest EU funding ever awarded to the industry and promises a step change from current modern methods of construction towards an era of inspirational, unconstrained design with ultra-efficient manufacture and industrial-style construction. Led by Corus Group (UK), the initiative is endorsed by the European Network of Construction Companies for Research and Development (ENCORD1) and in line with the European Construction Technology Platform (ECTP2) research agenda. In addition to the 10 million Euros of EU funding, the consortium will be putting forward an additional 40 million Euros. ManuBuild will complete demonstration projects across Europe, including two large residential buildings in Madrid (led by EMV3, the City Council of Madrid), a low-rise apartment building in Stockholm (led by NCC4) and a residential project and a healthcare or schools building in the UK (led by Taylor Woodrow Construction, TWC5). The latest development of a ManuBuild project by partner NCC for industrialized building component production in the most recent factory and on site factory in Europe is described in [2].

Figure 18: Concrete distribution at NCC factory(4)

ManuBuild envisions a future where customers will be able to purchase high quality manufactured buildings having a high degree of design flexibility and at low cost compared to today. For the first time, inspirational unconstrained building design will be combined with highly efficient industrialized production. ManuBuild targets a radical breakthrough from the current "craft and resource-based construction" to "Open Building Manufacturing", combining ultra-efficient (ambient) manufacturing in factories and on sites with an open system for products and components offering diversity of supply in the market:.

- Customers are actively engaged in the design of their buildings, using state of the art interactive tools
- Mass customisation, not mass production, offers customers increased choice and design flexibility
- Ultra-efficient, flexible and scalable manufacturing enables production efficiencies of industrialised scale
- An open system for products and components gives diversity of supply and competitive costs for components

Enabling business processes, ICT systems, new materials and technologies and smart components etc will underpin this development. Potential impacts include significant reductions in the number of construction industry accidents, waste and the costs and time to construct buildings. This will allow Europe to improve its building stock, whilst also releasing resources that can be allocated to other income generating industrial sectors.

Figure 19: Concrete panel logistics in NCC factory [4].

In the NCC (Swedish Manubuild partner) Komplett factory 60 operators work on job rotation time schedule. The yearly capacity is 1000 apartments and each worker is producing 17 apartments yearly. Automation and mechanization are ergonomically designed to reduce labour fatigue. Every 15 Minutes a truck leaves the factory. The apartments are 90% prefabricated. The investment was about 300 million SEK. The on site assembly factory is all weather proofed enabling ergonomic working conditions all year around. [3].

Figure 20: On site factory of NCC Komplett [4].

15 Conclusion

The research, development and application of industrialization to construction during the last 3 decades shows that by using robotic technologies in prefabrication, on site construction and services, we will be able to achieve customized building products at affordable construction costs and constant quality and human oriented working conditions.

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