AUTOMATION AND ROBOTICS IN CONSTRUCTION. STATE OF THE ART IN JAPAN

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ABSTRACT
This paper reports on the current state of the art in automation and robotics Research and Development (R&D) activities in Japanese construction industry. At present, building constructions are activated and a shortage of construction workers has been serious in Japan. Accordingly, there has been a growing need for automation and robotization of construction operation to overcome this problem.

R&D of construction robots are generally conducted by general contractors, however, the R&D was not in time to make the serious labor shortage relieved. Various kinds of automated construction equipments have been developed for construction field application in such areas as concreting and finishing operation, however, they are not practical enough. Recent R&D is concentrated in more practical and overall system automatization using robotic technology. A turning point is coming in construction Automation and Robotics in Japan changing R&D policy from stand alone robot development to system integration combining advanced technologies.

1. INTRODUCTION
From 1988, a prosperous economy prevails in Japan and investment in the construction industry is growing rapidly. Particularly in large cities, a lot of construction projects are being planned or are already under way. In such a circumstance, the shortage of skilled construction workers has become prominent, especially in building construction using formwork carpenters and reinforcing steel fabricators. The shortages of these workers have resulted in sharp increase in labor wages, thus creating further escalation in construction costs.

In 1982, research and development (R&D) in automation and robotics (A&R) for construction operations started in Japan, developing a construction robot to improve in operating efficiency, to eliminate works in hazardous environments, and to save labor force. Motivation at initial stage of R&D was to free workers from hazardous operations. The aims of R&D have been shifting to save manpower and improve productivity at sites. This R&D covers various aspects of construction work such as reinforcement assembly; placing, screeding, and finishing of concrete; erecting and welding of structural steel exterior finishing and painting; and interior finishing. Recently, automated construction systems applied robotic technology are experimented at several building construction and civil works. They could save manpower successfully to propose an advanced construction system for future generations.

The objectives of this paper is to describe the state of the art of construction A&R in Japanese construction industry.

2. BACKGROUND OF A&R SYSTEM DEVELOPMENT IN CONSTRUCTION
The basics of the background for automation and robotization of construction work have not changed for these years. However, the volume of construction work has increased rapidly during the past several years, due to which the shortage in skilled workers has become even more serious. Consequently, the need for further A&R in the construction industry is no longer an imagination but a reality which must be accepted.

Figure 1 shows investment growth of the construction industry in Japan. As can be comprehended from this chart, the amounts invested in construction have increased sharply in the past three years. Figure 2 shows the total contract amount of orders awarded by major Japanese construction companies (50 major contractors). These amounts have rapidly increased during the past few years, especially in building construction. Almost all construction companies which are interested in and promoting construction A&R are included in these 50 firms.

With such rapid increase in construction volume the shortage of construction workers has become more and more serious. Figure 3, shows the shortages of skilled labor for construction comparing to various industries. The ratio of shortage in the construction sector is higher than others, and this gap has increased after 1987. Skilled construction workers such as reinforcing steel fabricators, masons, and
formwork carpenters have risen to the highest level of shortage. As a consequence, delays in
construction projects have been common in Japan.

Under such circumstances, a strong demand for development of A&R systems enabling work to be done
with fewer workers rose in the construction industry. Development of practical construction A&R
systems to perform various construction works has become near term R&D goals for many contractors.

3. CONSTRUCTION A&R SYSTEMS DEVELOPED IN JAPANESE CONSTRUCTION INDUSTRY

Construction companies which are committing construction A&R are activated in A&R of construction
work for the past ten years. Unlike general purpose construction equipment, construction robots generally
have not been identified, and construction equipment manufacturers have taken negative attitudes to
robot development up to now. Therefore, major construction companies have assumed the leadership in
development of A&R in construction. Almost all these companies have researchers and construction
experts who are knowledgeable about actual on-job operations and interested in improving
construction systems introducing advanced technologies. These human resources have provided a strong
base for major construction companies to aggressively perform R&D in this area.

In the past several years, construction equipment manufacturers have joined the construction A&R
activity participating in producing hardwares cooperating with these construction companies. A&R
systems developed for construction work announced since 1982-1991 are listed on table 1.

To describe the features of recent development examples by type of work, a large number of cases are
concentrated in concrete construction-related works, and interior and exterior finishing related
operations. The cases of development are concentrated in floor concrete work, and automation and
robotization have been pursued to cope with the various steps of placing, screeding, and finishing. In
interior finishing, there are examples aiming for automation of fixing gypsum boards to ceilings, and
development of a manipulator for aiding in sticking boards to walls. For exterior finishing work, robots
that perform pneumatic application of coatings to the exterior walls of buildings have been developed
by three firms. Tele-operated equipments developed for simple operations, also called "Robot", were
developed and are on market.

4. CURRENT R&D TRENDS IN CONSTRUCTION A&R

4-1 System Automation

From 1990-1991, several construction companies have paid much R&D effort to introduce automatic
construction systems into actual sites. Their activity includes to establish a new construction method,
and to develop automatic equipments and computer management network for the system. Original
concept for the system automations has come from "Site Automation" which has been proposed before,
recent examples developed are the first 2 step for implementation(1).

From the industrial point of view, every trial at sites using a new method or approach are regarded as
one of the beneficial business. Robotics engineers and site managers involved in these R&D were so
successful overcoming various kinds of technical problems and tough negotiations from the initial stage
of planning through actual operations. There might be some contribution of their experience developing
stand-alone construction robots shown on Table 1(2), (3), (4).

4-2 Developing Multi-purpose Manipulator For Building Works

A lot of single task robots and prototype machines have been developed in these ten years. A new
trend is to use a multi-purpose manipulator exchanging endeffectors or tools for tasks. Applied tasks for
the manipulators are heavy components handling arm and mobile manipulator for vertical wall surface
works. Their performance and system architecture are completely different, however, they will be
more practical to be applies to many tasks obtaining potentials(5), (6).

4-3 Transportation Automation

At a large scale tunnel construction site and nuclear power plant construction site, advanced material
and component transfer systems automated by using robotics and computer technology were successfully
applied to save labor force and to shorten construction period. They could be a good example applied
factory automation engineering to construction material handling. Transfer system with sensors
feedback, computer network for planning and production control, robotic arms to pick up and position
components and information transfer code system have worked well under hazardous environment for
electronic components(7).

4-4 Research On Advanced Robotic Technology

Robotics engineers in construction companies are very aggressive to get an advanced robotic technology
such a fuzzy control, neural network, sensor fusion, flexible arm control and artificial intelligence.
These efforts are executed as an inhouse research at their institute however, a few examples became visible by their report papers(8), (9).

4-5 Accelerated R&D On A&R

Many construction companies are shifting their A&R to one of the major R&D targets in their companies, recruiting engineers in robotics, electronics and computer science. Their organization for A&R are including not only research institutes but also other divisions such as design, planning, engineering and construction to increase the capability applying A&R to their business(10).

Enhanced R&D potential for A&R could realize an overall advanced system integration for a tunnel construction and civil works. Reviewing these projects, many clients, governmental agencies and electric companies are understanding and heavily will be involved to promote A&R activity at their construction sites in the near future(11), (12).

5. CONCLUSION

Many Japanese construction companies have made an excellent developments on A&R in construction for these 10 years. Their efforts are directing more practical area from developments of stand-alone robot system for specific construction work. Recent phenomenon on construction A&R in Japanese construction industry indicates that A&R technology are supporting improved construction projects from an early stage in a sophisticated way.

Details of their advanced A&R system will be reported at technical conferences and in journals.

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(3) Shigeru Sakamoto, Taisei Corp., "Research and Development for Totally Mechanized Construction System for High-Rise Building"
(4) Junichiro Maeda, Shimizu Corp., "Research and Development on Automatic Building Construction System, 'Smart System"
(5) Yasunobu Miyazaki, Kajima Corp., "Development of 'Multiple Purpose Construction Hand"
(6) Shigeru Ohtsuki, Nihon Bisoh, "Development of Multi-Purpose Robot of Wall-Walkers"
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(10) Kazuhiro Ari, Kajima Corp., "Condition Arrangement for Application of Construction Robots"
(11) Hitoshi Sato, Shimizu Corp., "Reinforcing Bar Prefabrication Using CAD/CAM"
(12) Katsumasa Kawamoto, Kajima Corp., "Ground-level Remote Control System for Pneumatic Caisson"

(4), (5), (6), (7), (8), (11), (12): Proceedings of the First Symposium on Construction Robotics in Japan (Japanese), June 1990.
Figure 1. Investment in Construction

Figure 2. Total Contract Amount

Figure 3. Shortage Ratio of Skilled Labor
\[ S = \left( \frac{\text{Shortage numbers}}{\text{employee numbers}} \right) \times 100 \]
Table 1: Construction A&R System Developed by Japanese Construction Industries (1982-1991)  
(Prototype or Commercial Models)

<table>
<thead>
<tr>
<th>Building Construction</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Foundation</td>
<td></td>
</tr>
<tr>
<td>(1) Concrete Block Laying Robot</td>
<td>TO</td>
</tr>
<tr>
<td>(2) Automatic Piling System</td>
<td>AK</td>
</tr>
<tr>
<td>Material Handling</td>
<td></td>
</tr>
<tr>
<td>(1) Radio Control Auto-Release Clamps</td>
<td>OH, SH</td>
</tr>
<tr>
<td>(2) Steel Beam Positioning Robots</td>
<td>SH, TK, FU</td>
</tr>
<tr>
<td>Welding</td>
<td></td>
</tr>
<tr>
<td>(1) Steel Welding Robot</td>
<td>KW</td>
</tr>
<tr>
<td>(2) Stud bolt Welding Robot</td>
<td>KA</td>
</tr>
<tr>
<td>Reinforcement Bar Construction</td>
<td></td>
</tr>
<tr>
<td>(1) Gross Steel Reimforcement Robot</td>
<td>KA</td>
</tr>
<tr>
<td>(2) Reinforcing Bar Fabricating Robot</td>
<td>TS</td>
</tr>
<tr>
<td>(3) Automated Reinforcement Work System &amp; Control</td>
<td>OH</td>
</tr>
<tr>
<td>(4) Automatic Bar Arrangement &amp; Prefabrication Systems</td>
<td>SH</td>
</tr>
<tr>
<td>Concrete Works</td>
<td></td>
</tr>
<tr>
<td>(1) Placing Robot</td>
<td>TD</td>
</tr>
<tr>
<td>(2) Automatic Placing Crane</td>
<td>OH</td>
</tr>
<tr>
<td>(3) Horizontal Concrete Distributor</td>
<td>TK</td>
</tr>
<tr>
<td>(4) Concrete Distributing Crane</td>
<td>TK</td>
</tr>
<tr>
<td>(5) Concrete Floor Screeding Robots</td>
<td>TK, SH, FU</td>
</tr>
<tr>
<td>(6) Concrete Surface Finishing Robots</td>
<td>SH, KA, TK</td>
</tr>
<tr>
<td>(7) Concrete Chipping Machine</td>
<td>SH</td>
</tr>
<tr>
<td>System</td>
<td></td>
</tr>
<tr>
<td>(1) Roof Push Up Method for Office Building</td>
<td>TA</td>
</tr>
<tr>
<td>(2) Totally Mechanized Construction System for High-Rise Building</td>
<td>TS</td>
</tr>
<tr>
<td>(3) Automatic building Construction System, &quot;Smart System&quot;</td>
<td>SH</td>
</tr>
<tr>
<td>Finishing &amp; Assembling Work</td>
<td></td>
</tr>
<tr>
<td>(1) Spray Robot for Fireproofings</td>
<td>SH</td>
</tr>
<tr>
<td>(2) Ceiling Panel Positioning Robots</td>
<td>TO, SH, TS, KD</td>
</tr>
<tr>
<td>(3) Silo Interior Coating and Lining Systems</td>
<td>SH, FU</td>
</tr>
<tr>
<td>(4) Spray Robot for Exterior Wall Painting</td>
<td>SH</td>
</tr>
<tr>
<td>(5) Robot for Painting High Building Exterior Wall Coating System</td>
<td>TS, SU</td>
</tr>
<tr>
<td>(6) Board Placing Manipulator</td>
<td>TS</td>
</tr>
<tr>
<td>(7) Automatic Exterior Wall Spray Systems</td>
<td>SH, TK, KU</td>
</tr>
<tr>
<td>(8) Tile Setting Robot</td>
<td>HA</td>
</tr>
<tr>
<td>Inspection</td>
<td></td>
</tr>
<tr>
<td>(1) Tile Inspecting Robots</td>
<td>KA, TS</td>
</tr>
<tr>
<td>(2) Self Climbing Wall Inspector</td>
<td>TK</td>
</tr>
<tr>
<td>(3) Room Cleaning and Inspection Robots</td>
<td>TD, OH, KU, KO, HA, TB</td>
</tr>
<tr>
<td>(4) Auto Horizontal/Vertical Travel Equipment</td>
<td>NK</td>
</tr>
<tr>
<td>(5) Gas Pipe Inspection Robot</td>
<td>TG</td>
</tr>
<tr>
<td>(6) Automatic Inspection System for Pipe Corrosion</td>
<td>MI</td>
</tr>
<tr>
<td>(7) Wall Inspection Robot</td>
<td>OH</td>
</tr>
<tr>
<td>Cleaning</td>
<td></td>
</tr>
<tr>
<td>(1) Multi-purpose Travelling Vehicle</td>
<td>SH</td>
</tr>
<tr>
<td>(2) Window Cleaning Robots</td>
<td>MD, NB</td>
</tr>
<tr>
<td>(3) Duct Cleaning Robot</td>
<td>ME</td>
</tr>
<tr>
<td>(4) Automatic Laser Beam-guide Floor Robot</td>
<td>OH</td>
</tr>
<tr>
<td>(5) Auot-travel Floor Cleaning Robots</td>
<td>TA, AU</td>
</tr>
<tr>
<td>Multi-Purpose</td>
<td></td>
</tr>
<tr>
<td>(1) Multi-purpose Wall Walker</td>
<td>NB</td>
</tr>
<tr>
<td>(2) Multi-purpose Construction Hand</td>
<td>KA</td>
</tr>
</tbody>
</table>
### Ocean
- (1) Remote Control Underwater Surveyer: KO
- (2) Pebbles Smoothing Robot: KO
- (3) Submersible Walking Auto Dredger: PO

### Dam Works
- (1) Automated Form Work Systems: SC, NI, TX
- (2) Automated Concrete Decomposing Robot: KA
- (3) Remote Control Piling Robot: KA
- (4) Fully Automated Vehicle: TA, HA

### Tunneling Works
- (1) Concrete Spraying Robots: OH, KA, TE, TO, MI
- (2) Segments Assembling Robots: KU, TD, KA, NKK, MK, MJ, HI
- (3) Shield Excavating Robots: Mj, HZ
- (4) Auto Drilling Robots: FR, KU, MA, TA
- (5) Tunnel Solidized Measurement Machine: KU
- (6) Tunnel Reform and Lining System: TE
- (7) Automatic Segment Carrier System: SH
- (8) Concrete Chipping Robot for Tunnel Repairing: TEPCO
- (9) Sliding Press Lining Robot: FU
- (10) Automatic Direction Control System for Shield Machine Driving: MK
- (11) Fuzzy Controlled Shield Machine: OK

### Underground Works
- (1) Remote Controlled Excavation System for Pneumatic Caisson: KA

### Road Construction
- (1) Road Recovering Robot: KO
- (2) Pavement Cutting Robot: KD
- (3) Automated Road Paving Equipment: KR

### Bridge Works
- (1) Climbing Robot Jack System: FU
- (2) Spraying Robot: KJ
- (3) Remote-Controlled Under Ground Excavation System: TEPCO

### Nuclear Plant Demolishing
- (1) Biological Shield Concrete Wall Cutting Robot: SH

### Investigation
- (1) Concrete Compaction Measuring Systems: MB, FD

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**Companies:**
- AK: Asahi Chemical Industry*
- FR: Furukawa Sakuganki*
- HI: Hitachi Kenki*
- KB: Kawasaki Heavy Industries*
- KU: Kumagai Gumi
- MB: Mitsui & Company*
- MI: Mitsui Construction
- NB: Nihon Biso*
- NKK: NKK*
- SH: Shimizu
- TB: Tobishima
- TEPCO: Tokyo Electric Power*
- TK: Takenaka Koumuten
- TX: Takenaka Dobuko
- AU: Automax*
- FU: Fujita
- HZ: Hitachi Zosen*
- KD: Kandenko*
- KW: Kawata Kogyo*
- MD: Mitsubishi Electric*
- MJ: Mitsubishi Heavy Industries*
- NI: Nishimatsu
- OH: Ohbayashi
- OK: Okumura
- SU: Sugatec*
- TD: Toda
- TO: Tokyo Construction
- FD: Fudou
- HA: Hazama-Gumi
- KA: Kajima
- KO: Komatsu*
- KR: Kajima Rd
- MA: Mazda Motor*
- ME: Meidensha*
- MK: Maeda
- NK: JGC*
- PO: Penta-Ocean
- TA: Toshiba
- TE: Tekken
- TG: Tokyo Gas*
- TS: Taisei

*: not general contractor