1 Introduction

Single-task construction robots (STCRs) were developed predominantly for use on the construction site. After the first experiments in large-scale industrialized, automated, and robotized prefabrication of system houses were successfully conducted in Japan (see **Volume 2**), and the first products (such as Sekisui Heim's M1 prefabricated system) also proved successful in the market, the main contractor, Shimizu (1975, Tokyo), set up a research group to develop on-site construction robots. The goal was now no longer the shifting of complexity into a structured environment (SE) as in large-scale prefabrication (LSP), but the development and deployment of systems that could be used locally on the construction site to create structures and buildings. The focus initially was on simple systems in the form of STCRs that could execute a single, specific construction task in a repetitive manner. The fact that STCRs were task specific made them, on the one hand, highly flexible (they could be used along with conventional work processes and did not require the whole site to be structured and automated), but also represented a major weakness. The fact that in most cases they were not integrated with upstream and downstream processes and the need for safety measures because of the parallel execution of work tasks by human workers in the area where the robots were operating often counterbalanced productivity gains.

Above all, the setup of the robots on-site (equipment, programming) was time consuming and demanded new skills. The relocation of the systems on-site was in many cases complex and time consuming. Therefore, the evaluation of the first generation of developed and deployed STCRs and the identification of the aforementioned problems led step by step, from 1985 onwards, to the first concepts for integrated automated/robotic on-site factories that integrate STCRs and other elementary technology, such as subsystems, into SEs to be set up on the construction site. For this reason, the development of construction robot technology in general and in particular the concept of structuring on-site environments by means of robot-oriented design (ROD) were pushed forward. The conceptual and technological reorientation towards integrated automated construction sites was initiated by Waseda Construction Robot Group (WASCOR), which brought together researchers from all major Japanese construction and equipment firms. The first in-use phase of STCRs, as well as the conceptual reorientation from 1985 onwards, laid the technological and conceptual basis for the development and deployment of automated/robotic on-site factories in the following years.

The development of STCRs provided the basis and paved the way for the realization of integrated automated/robotic on-site factories from the 1990s onwards, and during the past decade, as a result of the flexibility and potential it provides, actually became once more a dominant research field in construction automation and robotics. The development of STCRs parallel to, or as subsystems of, integrated automated construction sites has continued to the present day, and a multitude of new robots have been developed since then and new categories have even emerged. With robot technology becoming more compact and lightweight, significant advances in human–robot interaction and cooperation taking place, and the capability and usability of software for the planning and execution of tasks growing more mature, STCRs are indeed becoming a more and more feasible solution also in less structured environments. The great advantage of the STCR approach is its flexibility and adaptability. It does not require turning the whole construction site into a manufacturing facility, is nonexclusive (and thus allows, if demanded, a focus on the robotization of only individual performance critical, dangerous, or labor intensive tasks), necessitates only a manageable amount of change in terms of construction procedures compared to conventional construction, and designed in the right way, STCRS can be adapted to a huge variety of different site conditions.

Although the STCR approach emerged in Japan, it is today a worldwide research, development, and application theme and STCR development is brought forward in the incumbent industrial nations (Japan, Europe, USA) as well as in catching up industries (in Korea, China, India, Russia, Poland, etc.). Furthermore, the task fields, approaches, and categories of STCRs broaden continuously. Whereas the first systems in Japan built on relatively simple manipulators and mobile platforms used to distribute concrete, finish floors, install wall panels, and move material, recently new forms of STCRs emerged building on aerial approaches, additive manufacturing technologies, exoskeletons, swarm robotic approaches, self-assembling building structures, and even humanoid robot technology.

1.1 History and Development of the STCR Approach

At the end of the 1970s, Shimizu and other Japanese general contractors conducting large building and infrastructure construction projects observed a huge potential in construction robots. Subsequently, with the beginning of the robotics boom in the early 1980s, in which automation and robot technology in all industries in Japan suddenly spread enormously (see also **Volume 1**), the theme became so relevant for the Japanese construction industry that it eventually led to the Japanese government starting, promoting, and bringing forward STCR technology. The chronic shortage of skilled workers in Japan was another reason. Finally, in 1978, the Japan Industrial Robot Association (JARA), under the guidance of the Ministry of Trade and Industry (MITI), established a commission headed by Professor Yukio Hasegawa for the analysis of such applications and the development of automated systems and robotic technology in construction. Participants of this commission were mostly young and motivated engineers from the major Japanese construction companies, and also included general contractors and machine builders. The commission quickly became a "germ cell" for new concepts, and step-by-step specific research projects and robotic systems were set up and implemented by companies.

Numerous universities followed this trend. Waseda University, for example, founded the legendary WASCOR group, which started developing automated and robotic construction technology using an interdisciplinary, cross-sector approach. Then, in the early 1980s, the coordinated activities of the large, national research institutes followed. In 1983, the Architectural Institute of Japan (AIJ) and its commission, responsible for building materials and construction methods, implemented a group (with 15 participating institutions including companies, associations, universities, and public bodies) for automation and robotics in construction. Shortly afterwards, the Japan Society of Civil Engineers (JSCE) followed, and from 1985 the renowned Building Research Institute of the Japanese Ministry of Construction (BRI) started to work with the Center for Development on systems for robotic assembly (e.g., Solid Material Assembly System [SMAS]). In 1987, the Building Contractors Society (BCS), whose members were once more the major construction companies, started with a systematic assessment of the need and potential of automation and robotic technology, in particular for subcontractors, equipment manufacturers, and construction equipment rental companies.

The reasons for the synergistic activities of government, national research institutes, general contractors, and academic institutions had both political and socioeconomic grounds. For example, the low productivity in the construction industry compared to the manufacturing industry, shortage of skilled labour, aging of construction workers, increasingly poor workmanship, rising work-related diseases, and poor working conditions were controversial topics of discussion for the public. The construction industry, which in Japan has traditionally had a high reputation in society, thus faced strong pressure to improve the working environment and the general image of the construction industry.

Figure 1.1 outlines the timeline of activity of the aforementioned institutions participating in the development of STCRs. All in all, the following institutions were involved in the development and deployment of automated and robotic technology during the 1980s and 1990s (first in the form of STCRs and later in the form of integrated automated/robotic on-site factories) for on-site building construction:

- Japan Robot Association (JARA)
- Ministry of Industry and Trade (MITI)
- Waseda Construction Robot Group (WASCOR)
- Ministry of Construction (MOC)
- Architectural Institute of Japan (AIJ)
- Building Contractors Society (BCS)
- Advanced Construction Technology Center (ACTEC)
- Japan Society of Civil Engineers (JSCE)
- Building Research Institute of the Japanese Construction Ministry (BRI)
- Research institutes of large construction companies (Shimizu, Obayashi, Kajima, Maeda, Goyo, Toda, Taisei, Fujita)
- Manufacturers of automation and robot technology

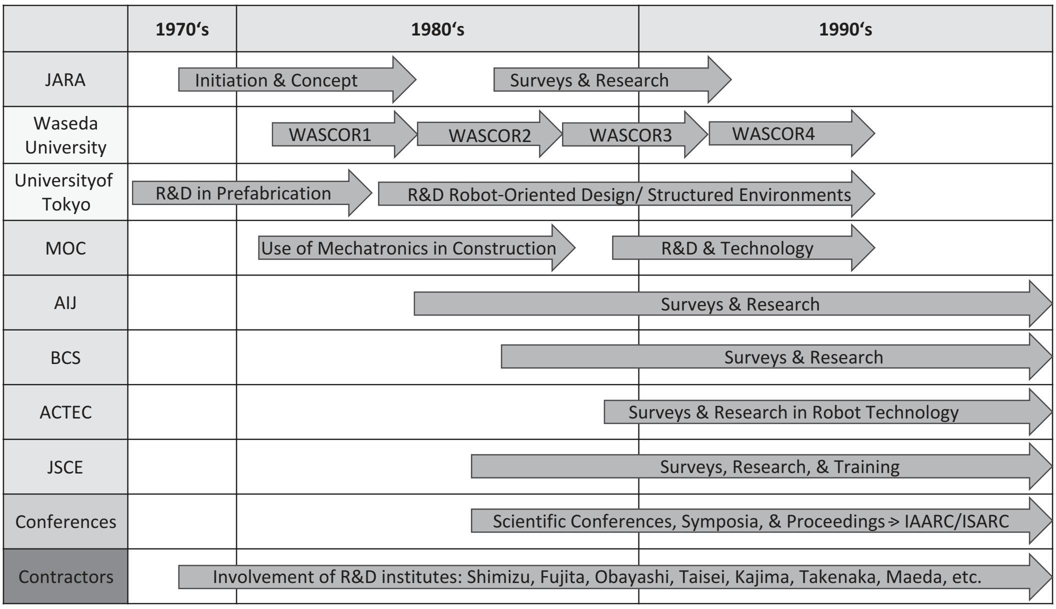


Figure 1.1. Timeline showing activity of institutions participating actively in the development of STCRs (refined and complemented with the authors' information on the basis of Cousineau & Miura 1998 and Hasegawa 1999.)

- Construction/manufacturing equipment suppliers (e.g., Komatsu, Hitachi, Mitsubishi, Kawasaki, Hazama, etc.)
- Universities: Waseda University, The University of Tokyo, etc.

The following research and development (R&D) investment sources contributed to automated and robotic technology (first in the form of STCRs and later as integrated automated sites) for on-site building construction during the 1980s:

- R&D budget of construction companies
- R&D budget of equipment suppliers
- Ministry of Construction (MOC)
- Manufacturers of automation and robot technology

1.2 Strengths and Weaknesses of the STCR Approach

STCRs are systems that support workers on the construction site in executing one specific construction process or task (e.g., digging, concrete levelling, concrete smoothening, brickwork construction, logistics, and painting) or by completely substituting the physical activity of human workers necessary to perform this one process or task. The processes and tasks assisted or executed by STCRs are in most cases relatively profession or craft specific. Furthermore, the processes and tasks for which STCRS were developed have in common that they necessitate a high rate of repetitive subactivities. Further common characteristics are as follows:

1. STCRs are developed predominantly for use on the construction site.

2. STCRs are highly specific, not only to a profession, but even to a task within a specific profession (e.g., different systems for concrete pouring, levelling, and smoothing, which all fall within the realm of the "floor layer" profession)
3. Enhanced productivity compared to conventional labour- and machine-based execution of work tasks:
   a. More m^2/hour than conventional execution (e.g., concrete floor finishing rate – labour based: 100–120 m^2/hour; concrete floor finishing rate robot: 300–800 m^2/hour, according to Cousineau & Miura 1998)
   b. Increased labour productivity
4. Positive impact on quality through precise control of functions and operations (e.g., uniform distribution of paint) and by allowing execution to be recorded or monitored in real time
5. Improvement of working conditions: reduction of dangerous and heavy physical work
6. Various operation modes allowed by most robots: automatic sensor-guided, automatic preprogrammed, remote controlled
7. Positive impact on resource consumption through precise automatic control (e.g., painting robots ensuring that the amount of paint was precisely controlled and that spare paint was collected and reused)
8. In most cases, simple but robust sensor technology: gyroscopes, simple laser measuring systems, touch/pressure sensors, and so forth
9. In many (but not all) cases no more than one operator required to supervise the systems (Systems supervised by two or more persons are inefficient; for further explanation, see **Volume 1.**)

As in any other industry, concepts of modularity developed slowly and step by step over time. Modularity, and thus adaptability to multiple work processes or tasks, was not a characteristic of STCRs in the beginning. This reduced the operational scope of the systems and increased the cost of the robot systems, despite the aforementioned benefits; as such, it not possible to distribute that cost over various work activities (as with conventional multipurpose construction equipment, for example). Some companies introduced modular approaches only in later robot generations, such as by allowing for end-effector change.

The fact that STCRs are task specific makes them on the one hand highly flexible (they can be used along with conventional work processes and it is not necessary for the whole site to be structured and automated), but also presents a major weakness. In most cases they are not integrated with other construction processes, which demands safety measurements and hinders parallel execution of work tasks by human workers in the area where STCRs are operated. As a result, productivity gains are often counterbalanced. Above all, the setup of the robots on-site (equipment transport, task setup/programming) is time consuming and demands skills that extend beyond those of today's construction workers. Furthermore, the relocation of the systems on-site is in many cases complex and time consuming.

Indeed the evaluation of the first generation of developed and deployed STCRs, and the occurrence of the aforementioned problems (which continued technological development today makes it more and more possible to overcome), led step by step from 1985 onwards to the concept of automated/robotic on-site factories. Although

STCR technology was incrementally improved during the 1980s and the 1990s and advanced from the so-called first-generation robots to second- and third-generation robots (outlined in more detail in Cousineau & Miura 1998), the automated/robotic on-site factory approach (given the state of the technological development in robotic and related fields at that time) provided better possibilities to reduce work task spectrum and human labour as well as prestructuring the environment as the basis for higher automation ratios and just in time, just in sequence strategies, such as for factory internal component processing.

However, recent approaches show that major Japanese construction companies today are returning more and more to single-task–like approaches. Obayashi, for example, at present no longer uses its integrated, automated construction site (automated building construction system [ABCS]) as a total system, but applies some of its subsystems as STCRs (e.g., automated logistics systems, welding systems; for further details, se**e Volume 4**). By not directly and rigidly connecting those systems, Obayashi gains workshop-like flexibility (in contrast to chain-like organizations to which integrated sites were formerly oriented), which is necessary when constructing buildings such as the Tokyo Skytree, which changes its shape several times from bottom to top. New management approaches, acquired knowledge about the deployment, work process integration of single robotic or automated applications, digital work process management, and increasing usability of the software and interfaces used to set up the tasks to be executed by STCRs today positively influence the integration of such systems in the overall construction process and enhances STCR efficiency compared to the first-generation systems deployed during the 1980s. The development and deployment of STCRs thus is now, when more and more individuality of a product is demanded, more relevant than ever before.

1.3 Analysis and Classification Framework

In the context of producing this volume, STCRs were analysed according to the following framework:

- Background behind development
- Operational capacity
- Technical description
- Control strategy and informational aspects
- Dimensions and workspace
- Description of the robot-supported construction work process and comparison with the conventional work process
- Analysis of the composition and kinematic structures

On the basis of the analysis, 24 categories for task-specific on-site construction robots (STCRs) were defined:

1. Automated site measuring and construction progress monitoring
   a. Mobile robots
   b. Aerial robots
2. Earth and foundation work robots
3. Robotized conventional construction machines

4. Reinforcement production and positioning
5. Automated/robotic 3D concrete structure production on the site
6. Automated/robotic 3D truss/steel structure assembly on the site
7. Bricklaying robots
8. Concrete distribution robots
9. Concrete levelling and compaction robots
10. Concrete finishing robots
11. Site logistics robots
12. Aerial robots for building structure assembly
13. Swarm robotics and self-assembling building structures
14. Robots for positioning of components (crane end-effectors)
15. Steel welding robots
16. Facade installation robots
17. Tile setting and floor finishing robots
18. Facade coating and painting robots
19. Humanoid construction robots
20. Exoskeletons wearable robots and assistive devices
21. Interior finishing robots
22. Fireproof coating robots
23. Service, maintenance, and inspection robots
24. Renovation and recycling robots

The classification follows a work-task oriented approach, as the analysis shows that STCRs do not introduce new organizational settings, but aim at supplementing existing work tasks in conventional and at best slightly altered construction environments. The categorization thus refines and extends existing classifications (Bock 1989; Cousineau & Miura 1998) that followed a similar strategy but did not (as the development continued since then) cover the amount and variety of STCRs considered in this volume. A focus in this volume is on construction robots used on-site to construct buildings. Construction robots used off-site as well to construct, for example, civil infrastructures such as roads, bridges, tunnels, and so forth, are not considered in this volume.

The analysis of STCRs was conducted on the basis of a large picture and information archive; technical data; technical drawings and STCR analysis methodologies introduced by Bock (1989); and technical data, product description brochures, and background information provided by companies and researchers in charge of the development of individual systems. A further but incomplete source with detailed technical drawings was the *Construction Robot System Catalogue* (1999) published by the Japanese Robot Association. Detailed analyses and comparisons of a limited amount of concrete finishing robots, facade painting robots, facade inspection robots, and interior finishing robots by Cousineau and Miura (1998) completed general and technical information of the analysis of systems in those categories. Helpful for the identification of robots developed before the year 2000 was also the catalogue *Robots and Automated Machines in Construction* published by the board of directors of International Association for Automation and Robotics in Construction (1998). Helpful for the identification of robots developed *after* the year 2000 were the *Proceedings of the International Symposium of Automation and Robotics in*

Construction based on a conference at which the "who's who" of specialists involved in the development of construction automation systems and robots meet on a yearly basis.

1.4 Analysis of Composition of STCRs

1.4.1 Basics of Robot Composition

An overview and introduction to robot composition is given in **Volume 1**, where an overview of definitions, facts, and figures and the evolution of automation and robotics, as well as the relevant state of the art of knowledge (robot composition strategies, robot kinematics, actuators, sensor and process measuring technology, end-effector technology) is provided, and concepts such as modularity, human–robot cooperative manipulation, open source in robotics, and robotic self-organization are introduced. Within each thematic field, automation and robotics are addressed in general as well as construction-specific issues and applications. Furthermore, concepts, robotic technologies, and developments relevant for highly flexible production settings (e.g., inbuilt flexibility and modular flexibility of kinematic main structures and end-effectors, open source, fast reprogrammability, cellular approaches) that allow for product individualization in general and/or industrialized customization in the construction industry (e.g., in off- or on-site factories) are highlighted.

1.4.2 Robot Composition and STCRs

Robot compositions in different fields (e.g., general manufacturing industries, aircraft industry, shipbuilding industry, building component manufacturing, building prefabrication, the STCR field, automated/robotic on-site factories) possess similarities and also significant differences. Similarities can be observed, for example, concerning the increasing utilization of modular approaches and human–machine cooperative approaches. Differences result mainly from the scale and type of materials and components to be handled, resulting in different types of end-effectors and kinematic structures.

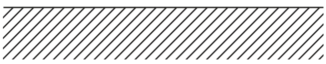
The following fields are relevant for setting the robot composition in STCR systems:

1. Working direction of the system (along the facade, from overhead, etc.)
2. Mobility approach (omnidirectional mobile platform, rail guided, fixed, etc.)
3. Kinematic structure (number of degrees of freedom [DoFs], geometric organization of links, etc.)
4. End-effector design (level of inbuilt dexterity, etc.)
5. Modularity of the system (exchangeability of end-effectors, drive units, and other parts)
6. Sensor systems (parameters sensed, local sensors, global sensors, complexity/accuracy/cost of sensors used, etc.)
7. Control mode (remote controlled/supervised, automatic, human–robot cooperative)

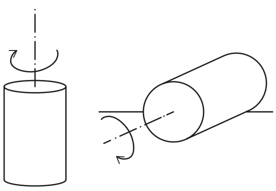
Kinematic structure analysis related to STCR studies the motion of different parts of robots to eventually get the desired on-site task done by the end-effector. Different types and the numbers of joints are studied along with links, which are rigid connections between joints. There are two basic kinds of joints in robots: translational (prismatic) and rotational (revolute). STCRs work in a more dynamic environment, in contrast to many other types of robots (such as industrial robots in the general manufacturing industry, which often are fixed and perform repetitive tasks in an SE). Most STCRs are required to move along defined trajectories or with defined areas and thus to utilize some sort of mobility providing mechanism. Examples of kinematic structures (Figures 1.2 to 1.18) are given in the following section for some STCR systems to provide a better understanding of the motion and degrees of freedom for STCRs of different categories.

1.4.3 Symbols and Representations of Kinematic Structure of STCRs

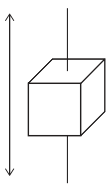
The kinematic diagrams of the robots are drawn partially by following the standard symbols and representations and partially using necessary additional symbols that are self-explanatory.



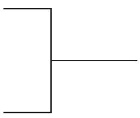
This represents a fixed base of a robot. This is always a first link of the system, that is, link 0.



This represents a rotary joint of the system. The dotted line shows the axis of rotation. The joint is usually labelled J_i and rotation arrow θ_i.



This represents a translational joint. The arrow on its side represents the direction of sliding. It is also denoted as J_i and the direction of displacement as d_i.



This represents the end-effector of the system. It follows the last joint and is shown directly connected with it.

This represents a system able to move. A base on the circles represents a robot equipped with a mobile platform.

1.4.4 Comparison of Kinematic Structures of STCRs

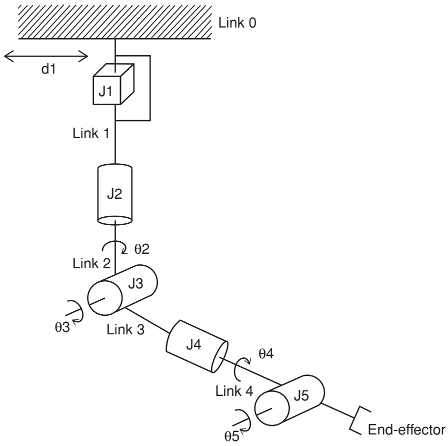


Figure 1.2 Overhead rail-guided digging robot, Shiraishi.

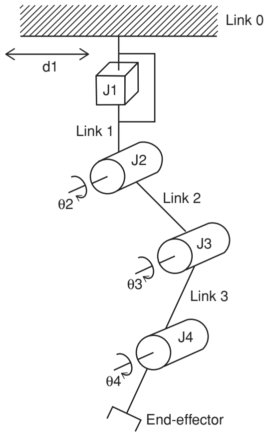


Figure 1.3 Overhead rail guided digging robot, Mitsui.

Earth and Foundation Work

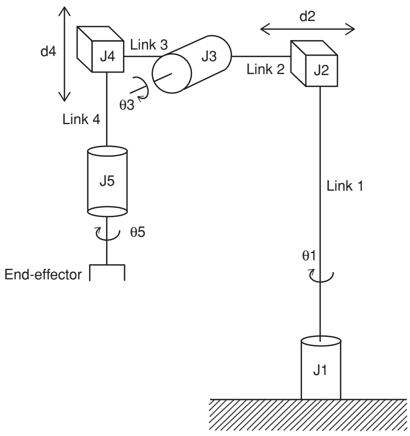


Figure 1.4 Automated crane for rebar positioning, Takenaka.

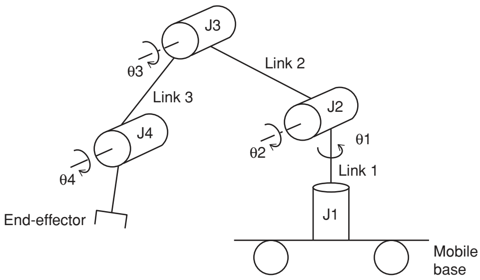


Figure 1.5 Robot for positioning heavy rebar, Kajima.

Reinforcement Positioning

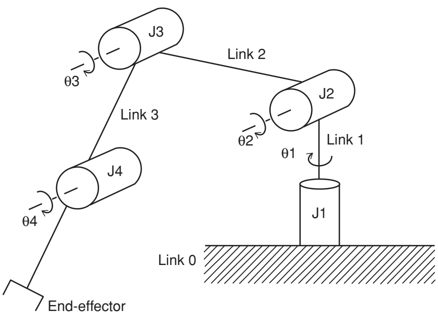


Figure 1.6 Stationary concrete distribution robot, Obayashi and Mitsubishi.

Concrete Distribution