Construction Robotics enabling Innovative Disruption and Social Supportability

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ABSTRACT

Productivity indicators in industry suggest that conventional construction methodology has reached its limits. This is true even in highly developed nations, where numerous construction projects cause considerable time, quality and cost deficits. This indicates the necessity of an overdue transformation of the whole sector—in particular of its procedural and technological aspects. Future construction could make use of what other manufacturing and service industries have already successfully implemented. This paper describes the relation-ship between the stagnation and technical limits of conventional construction and the initiation, development, and growth of new strategies and technologies of construction automation and robotics. In the future, construction automation technology, STCR-approaches, service robot systems and other microsystems technology are merging with the built environment, becoming inherent elements of buildings, building components, and building furniture. It can be said that it becomes ubiquitous, and starts pervading our life on earth and in particular built environments. Since this diffusion of robot technology is in most cases strongly linked to the built environment, future activity fields for construction automation will derive from this.

Keywords –

Construction Automation, Robotics in Construction, Ambient Integrated Robotics, S-Curves

1 Introduction

The welfare and development of every society depends on the economic sufficiency of its citizens. Every nation values efficiency in order to achieve as well as to sustain productivity and economic growth. Where there are no natural resources to be exploited and sold, high economic sufficiency can only be accomplished via sophisticated technology. Moreover, affordable and efficient socio-economical and socio-technical processes are also required by age-related demographic change. It is estimated that half of a nation’s total investment is allocated to the built environment, viz., infrastructures and facilities, signifying as well as emphasizing the strategic importance of the construction sector. Studies strongly suggest that productivity in the construction industry has been declining in recent decades worldwide (see Figure 1). The construction industry has one of the lowest capital investment as well as low capital intensity compared to other industries. Moreover, inappropriate working conditions—may these be related to sub-par human conditions or to technological inadequacies—as well as a low interest in the construction sectors shown by younger generations, the tremendous consumption of raw materials and energy (see Figure 2) by the construction process and building products etc., represent challenges for which conventional construction and architecture industries currently do not have solutions for. Furthermore, defect rates, cost overruns, and the ineffective as well as inefficient effort put into management strategies [1] to encounter these issues suggest that conventional construction has reached its possible technological performance limit [2].

In highly developed nations, the natural ageing of societies will continuously aggravate the situation by reducing human capital as well as the ability to implement change and boost economic growth. To ameliorate the situation, Börsch-Supan—a German macroeconomist—proposes a solution for augmenting productivity and economic wealth predominantly by supplementing human capital with capital intensity, non-linear advances in machine technology, and productivity [5]. Strategies coming from general manufacturing industries under the notion of “Industry 4.0” (see for example [6]) or “Cognitive Factory” (see for example [7]) call for hyper-flexible and intensively automated manufacturing systems (also considered as the 4th industrial revolution)—in which highly autonomous, flexible, and distributed but still networked automation and robot systems cooperate together to produce in a near real-time manner individualized and complex products with consistently sustained productivity—that promise higher productivity and needed change in a construction industry that has been stagnating for decades. Innovation in construction industry occurs extremely slowly. One of the key reasons for this is the involved multi-faceted characteristics of the products and their complexity, long life-cycle, diversity of dimensions and materiality, as well as the fixed-site nature of construction. Additionally, the low R&D budgets and the industry's reluctance to adopt new strategies and technologies represent a de facto limitation. In opposition to the marginal improvements in conventional construction, since the 1970s scientists, R&D departments, and innovative companies supported by universities, associations and governmental institutions, consistently pursued a new set of technologies and processes which will change the whole course and idea of construction in a fundamental way, and which can be summarized under the term "Construction Automation" (CA).

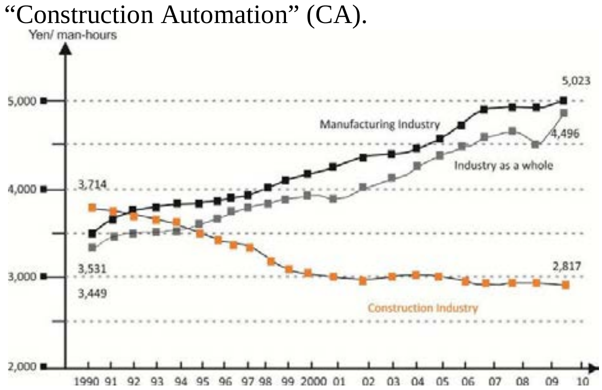

Figure 1. Labor productivity in manufacturing vs construction (image on basis of [3, 1])

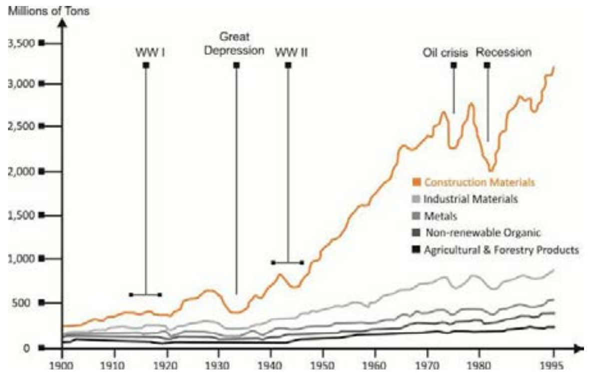

Figure 2. Raw Material Consumption (short tons) in the United States 1900-1995 (image on basis of [4, 1])

In contrast to conventional construction, CA is capital intensive and machine centred while being potentially limitless with respect to performance and capable of real-time manufacturing [1]. As CA necessitates a complementary and also disruptive change industry-wide (products, processes, organisation, management, stakeholders, business models etc.), it can be considered as a rather complex type of innovation or change as to allow it a pertinent developmental depth and breadth in order for it to fully unfold its potential. Changes of such complexity take time—sometimes decades. However, now after nearly 40 years of technical development and experimenting in the field, the result is increased activity within companies, research institutes, associations, and governmental institutes. This indicates that this new trend and the adoption of the future technologies involved become increasingly acknowledged and accepted, which allows it to head towards a growth phase.

Bock and Linner [2] categorized new design, innovation management methodologies, and enabling technologies that are essential to the realization and implementation of future CA as follows: (1) Robot Oriented Design, (2) Robotic Industrialization, (3) Construction Robots, (4) Site Automation, and (5) Ambient Robotics (see Figure 3). The following sections summarize and outline these key concepts, and show how future technological disruption could be implemented as well as how construction robotics might finally diffuse into a variety of areas of life.

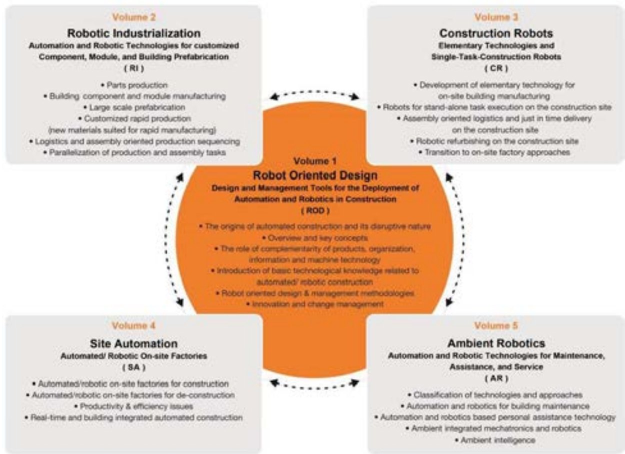

Figure 3. Key concepts for future automated construction as outlined in the Cambridge Handbooks in Construction Robotics Series [2].

2 Robot Oriented Design: Design and Management Tools for the Deployment of Automation and Robotics in Construction

Robot Oriented Design (ROD) and Management enable the efficient deployment of advanced construction and building technology. It is concerned with the co-adaptation of construction products, processes, organisation and management, and automated or robotic technology, so that the use of such technology becomes applicable, simpler and/or more efficient. It is also concerned with technology and innovation management methodologies and the generation of life-cycle oriented views related to the use of advanced technologies in construction and building context. The concept of ROD (see also Figure 4) was first introduced in 1988 in Japan by Bock [8] and served later as the basis for automated construction and other robot-based construction sites around the world. It was developed for improving the construction sector and adjusting conventional construction processes and component design to the needs of the novel tools [2].

Figure 4. The concept of Robot Oriented Design applied in an automated construction site (SMART) of the company Shimizu.

3 Robotic Industrialization: Automation and Robotic Technologies for customized Component, Module and Building Prefabrication

For robotic industrialization, concepts, technologies and developments in the field of Building Component Manufacturing (BCM) based on concrete, brickwork, wood, and steel as building materials and Large-scale Prefabrication (LSP) holding the potential to deliver complex components and products are key elements. BCM refers to the transformation of parts and low-level components into higher level components by highly mechanized, automated or robot supported industrial settings and it can be clearly distinguished from the manufacturing of high-level building blocks, such as building modules (prefabricated bath modules or assistance modules which can also be referred to as building subsystems) and building units (such as the prefabrication of fully finished three-dimensional building sections, like Sekisui Heim, Toyota Home, Pana Home, Misawa Hybrid etc., see also Figure 5). For highly automated prefabrication, according to the Original Equipment Manufacturer (OEM) model, component manufacturers represent Tier-1 or Tier-2 suppliers. Tier-1 suppliers would deliver components directly to companies such as Sekisui Heim, whereas, Tier 2 suppliers would supply the suppliers of the bath or assistance units. For Automated/Robotic On-site Factories, component manufacturers again represent Tier-1 or Tier-2 suppliers. BCM and LSP industry can reduce on-site complexity and build the supply backbone in an OEM-like industry structure, which can be considered also as a prerequisite for the successful implementation of Automated/Robotic On-site Factories. (for further information, see [1, 9])

Figure 5. The concept of Robotic Industrialization applied by the company Sekisui Heim to industrially personalize buildings on the assembly line (Image: courtesy of Sekisui Heim).

4 Construction Robots: Elementary Technologies and Single-Task-Construction Robots

After the first experiments in large-scale industrialized, automated and robotized pre-fabrication of system houses were conducted successfully in Japan, and the first products (e.g. Sekisui M1) also proved successful in the market, the main contractor Shimizu set up a research group for construction robots in Tokyo in 1975. The goal was now no longer the mere shifting of complexity into a factory environment, but the development and deployment of systems, which were able to be used locally on the construction site to create structures and buildings. The focus initially was set on simple systems in the form of Single Task Construction Robots (STCRs) that can execute a single, specific construction task in repetitive manner (see also Figure 6). The fact that STCRs operated task specific made them initially highly flexible (they could be used along with conventional work processes and did not necessitate that the whole site is structured and automated), but also represented a major weakness. As they were, in most cases, not integrated with upstream and downstream construction processes, which demanded safety measurements and hindered parallel execution of work tasks by human workers in the area where they were operated, productivity gains were often equalized.

The evaluation of the first generations of developed and deployed STCRs and the identification of the above mentioned problems led step-by-step from 1985 onwards to the first concepts for integrated automated/robotics sites. Concepts for Site Automation integrated STCRs and other elementary technology as subsystems into a controlled, factory-like environment set up on the construction site. (for further information, see [1, 8, 10])

Figure 6. Single Task Construction Robot applied by the company Taisei to automatically coat and paint the façade of a high-rise building

5 Site Automation: Automated/ Robotic On-site Factories

The approach of setting up controlled, factory-like environments on the construction site in the form of Automated/Robotic On-site Factories (see also Figure 7) can be considered as a logical step forward in prefabrication approaches and STCRs technology. 30 different Site Automation systems can be identified resulting in an application of Automated/Robotic On-site Factory technology about 60 times. 13 categories of Site Automation systems can be distinguished (10 categories for construction and three categories for deconstruction [1]). One of the main ideas for setting up automated on-site factories was to integrate stand alone or STCR technology into controlled on-site environments to networked machine systems and to improve organization, integration and material flow on the construction site (for further information, see [1, 8, 11]).

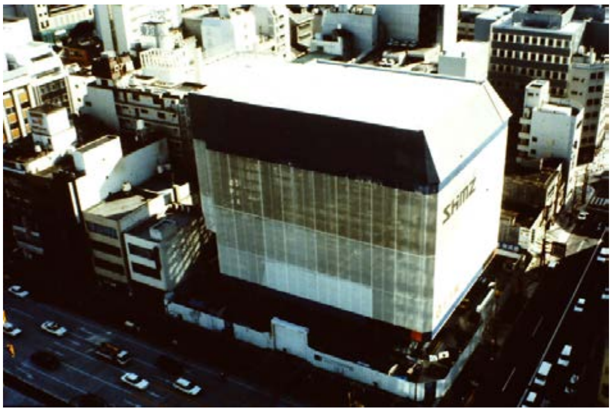

Figure 7. Outside view of an Automated/ Robotic On-site Factory (SMART) of the company Shimizu

6 Ambient Robotics: Technologies for Maintenance, Assistance and Service

Following the above detailed concepts and developments, it can currently be observed that CA technology, STCR-approaches, service robot systems, and other microsystems technology are merging with the built environment becoming inherent elements of buildings, building components, and building furniture. Clearly, this tendency can be observed in the design of future care environments. By an interdisciplinary approach, optimized care environments are developed in which service robotic systems are seamlessly interacting with the physical environment, embedded medicals sensors and subsystems, various sets of standardized and non-standardized processes and human beings (care takers as well as care givers). This enables multidimensional assistance and a broad set of modular and customizable services. The basic idea consists of a distributed layered architecture enabling omnipresent communication, and an advanced human–machine communication protocol [12]. The Ambient Intelligence (AmI, see for example [13]) paradigm sets the principles to design a pervasive and transparent infrastructure capable of observing people without interfering into their lives, adapting to the needs of the user. It must be noted though that populating a home environment with robotic elements must be performed following a space-efficient utilization scheme. Elderly people, and especially the ones using assistive devices such as wheelchairs and rollators, require increased barrier-free space for mobility purposes. Ambient Robotics focuses on the co-adaptation and the creation of compatibility (in a physical and informational sense) of assistive environments and service robot systems [14]. In contrast to conventional service robot development (see, for example, Care-O-Bot, Patient Transfer Assist, RI-MAN, see for example [15-17]) complexity of functions (hardware, software, tasks, etc.) will not be concentrated solely in the robot system but distributed strategically between robot system and environment. Previous research by the author showed, that such an approach has the potential for significantly reducing the complexity and the cost of the service robot system, enhance their reliability/robustness and above all create completely new service and assistance capabilities [18]. In the following sections (6.1-6.4), examples for four Ambient Robotic systems are outlined that were developed by the author in collaboration with industry and other research partners within a variety of research projects.

6.1 Mechatronic assistive system for health monitoring and training

The integration into living environments and user acceptance of high-tech mechatronic assistive functions has been difficult to achieve to date and real world deployment of such systems is rather rare. Therefore, in the particular implementation, a selected set of sensors, actuators and human-machine-interaction systems was integrated into a chair, which shall in real life serve as the center of life for a specific group of ageing people. The system followed a so-called “overlay approach”, which integrates advanced technology into well-known and proven objects of daily living in order to achieve user acceptance. A major challenge was the fusion of sets of technologies such as high performance medical sensors (i.e. for measuring EKG, Blood pressure, weight and activity), interface components, mechanical systems, sports and activity equipment, system monitoring sensors and an underlying data-management platform into a fully integrated and robust operating system.

A variety of research methods including usability studies, experimental optimization and integration were combined. The system (Figure 8) was also conceived together with the research departments of the involved firms as “products” embedded not only into daily activities, but also into the economic structures needed for large-scale deployment. All in all, the results clearly showed that user acceptance depends on the involvement of and tailoring of the system to the correct user group and on standards for the integration of systems from a variety of domains [19].

Figure 8. Outside view of an Automated/ Robotic On-site Factory (SMART) of the company Shimizu

6.2 Assistive robotic terminal for independent living

Due to natural aging processes, in a biological/medical and cognitive sense, it is more difficult for people to master Activities of Daily Living (ADLs) on their own [20, 21]. If an individual loses the ability to self-maintain at home, care in nursing homes or by a family member is usually necessary. ADLs refer to basic tasks of everyday living, such as eating, bathing, dressing, toileting, and transferring. When people are unable to perform these, they require assistance in order to cope, either from other human beings, or assistive devices, or both. Although persons of all ages may have problems performing the ADLs, prevalence rates are much higher for the elderly than for the nonelderly. Within the elderly population, ADL prevalence rates rise steeply with advancing age and are especially high for persons aged 85 and over [20]. However, the demographic change problem in Germany, but also present in other leading industrial nations such as Japan, Korea and China, leads to an overload for the family members and institutionalized nursing systems. At the same time, a reduction in financing for older people is observed, as well as in the economic productivity within Germany, as there are fewer employed productive individuals [22].

Some researchers have already proposed approaches to integrating mechatronics and robotic technologies into environments and to create robotized environments. Robotic Rooms [23], Wabot House [24], and Robot Town [25], have investigated the important basic approaches and foundations in this field of research. Robotic environments differ in regard to complexity, quality and multi-dimensionality of possible assistive functions relative to the classic "smart home" approach. However, these approaches primarily integrate sensors, actuators and robots on an informational level. Furthermore, they are presenting implementations that are realized in a controlled experimental environment, and cannot be straightforwardly applied into a regular medium sized apartment to serve as an integrated assistive system for ADLs.

In order to further describe the ideas presented above, we here detail key features of the smart wall terminal prototype. It was initially foreseen to discreetly embed all assistive functions in a terminal wall system. Considering residential environments and renovation processes, in terms of the age-appropriate adaptation of existing buildings, particularly in Europe and especially in Germany, the volume of construction associated with the current building stock already exceeds the volume of new construction. This shows that an approach that requires serious adaptation and refurbishment of the interior arrangement and layout, in order to transform existing walls into smart-walls is impractical because it requires expensive demolition of the existing installations. The so-called "Terminal-Wall" approach was gradually developed. Based on this approach, a smart wall focused on pre-embedding assistive functions in a modular element as a kind of furniture or cabinet, which can be later installed in the room without requiring refurbishment of the existing interior was developed. Because of the concentration of the assistive functions in a single terminal, a compact element arises which is efficiently produced and can be easily installed within the apartment. Consequently, a comprehensive product architecture was created, physical-wise and information technology-wise, as well as a furniture-like wall element, (Figure 9), which creates the basis for the various offered services and functions: a) an intelligent ambient lighting system, b) a mobile robotic rover (Turtlebot) as an intuitive user-machine interface [18], c) an air quality purifying system, d) a standard touchpad interface (tablet PC) for real-time display of navigation and weather information, e)•a reminder-alerting RFID-based monitoring system, f) user vital signs display and measurement system, g) a shoes putting on/taking off assisting system, h) assistive standing-up, sitting-down system. The control of the terminal can be done directly on the mirror in the middle of the terminal, (via two dedicated touch screen display areas, or via a tablet PC (Figure 9). The aforementioned services enable an innovative robotic terminal that functions towards autonomous and independent performance of ADLs in the home environment [26]. The terminal combines technologies of tele medicine, mobile robotics, machine-vision, sensor fusion, human-machine communication, etc., that provide elderly people with self-determined and independent living. In addition to numerous experimental tests and practical experience, a real-life apartment-based long-term study has been conducted in collaboration with users.

Figure 9. Smart Wall Terminal Prototype

6.3 Intra-house mobility, logistics and transfer assistance via robotic systems

For active and healthy ageing as well as relief for the relatives of aged individuals, novel mechatronic and robotic solutions are necessary for intra-house mobility logistics, and transfer. The objective of an ongoing study is therefore, to identify, analyze and validate concepts for the aforementioned concerns, in order to develop systems and design processes which will support elderly people within their home environment. A particular focus is put on the automation of such processes.

It can be concluded that for the automation of these processes the environment (a set of furniture, layouts, appliances, etc.) in which the robotic system or mobile platform propagates must be structured (similarly as in a factory environment) and re-designed for simplifying operations and operation variability [14]. Figure 10 depicts the proposed research concerns, which can enable a fully robot assisted care environment realization.

6.4 Cloud manufacturing production in a home environment by an assistive robotic based workstation

The idea of assistive workstations can be connected to a new structural and technological concept called Cloud Manufacturing (CM) [27]. Since the mid-1980s, this new concept has been exploited in research laboratories around the world, comprising ICT-based manufacturing technologies such as desktop production, desktop assembly, 3D-scanning, collaborative robots, tele-presence and autonomous mini-factories. The elderly can be considered as an important labour force for future industrial development especially in European highly industrialized nations, in particular in the context of design and production of value-added, personalized products/services that demand skilled and experienced labour. In this context, scenarios for the utilization of Cloud Manufacturing technologies are classified, and evaluated. The research team of the author developed and prototyped an exemplar novel assistive robotic workstation (Figure 11) for the elderly allowing them to produce personalized products, in a decentralized manner.

Figure 10. Robotic Systems for mobility, logistics and transfer assistance.

The assisted workspace integrates a set of advanced technologies [28, 29] into a complex system: a) a Telepresence System, b) Kinova’s JACO robotic arm, c) mechatronically-actuated shelves, d) vital signs measurement technologies, e) Vuzix smart glasses for augmented reality based assistive services, f) a robotic mobile platform for logistic support. g) laser scanning and h) a 3-D printer. The integrated systems of the desktop manufacturing mini factory allow “one of a kind” production of highly complex, customized products. In order to tailor the workstation to the needs of the target group (older workers and elderly people), the assistive CM workstation was prototyped with all its functions, and two field tests with real test persons were conducted. The field tests were conducted in the experimentation lab of the authors, where the workstation was prototyped and thus a real world assembly scenario was simulated. Field test 1 was conducted in the first half of the project (7 test persons/N=7, focus more on open questions, behavioural analysis as well as scenario and functional modules improvement), and field test 2 (21 test persons/N=21, focus assembly scenario, structured questions and usability evaluation of various human-system interaction/control modes) in the final phase of the project. The outcomes of the systematic evaluation conducted within each field test were subsequently used to improve the system [30].

Figure 11. Developed assistive CM workstation.

7 Robot Technology Becomes Ubiquitous

By observing advances within robot technology, it is feasible to predict that robot technology will experience a similar development as did the personal computer during the nineties. Experts and masterminds, as for example Bill Gates, announce the era of robotics and estimate that robotics becomes an inherent element of our everyday life. The South Korean government recently announced that it supports heavily the development of robot technology having the goal to establish at least one robot system in each household.

In 1961 Joe Englberger already criticized the focus of robot developers and industry on robots for manufacturing and stated: "The biggest market will be service robots" [31], asserted Englberger, who started the industrial robotics era when his firm (Unimation) delivered GM's first robot. Currently, robots are becoming more user friendly, less expensive, task adaptable, smaller, more widely distributed, and seamlessly integrated into work processes and devices. Individuals today are able to acquire modular kits of open source robot hardware, and interface robot systems directly to a computer via USB devices. The modern options make transitions between self-contained devices, such as the classical 6-DOF industrial robots, much simpler. Currently these types of machines, automation systems and robotic technology, are advancing in such a way that the differences are becoming seamless. There are examples of robots that have become no longer visible. The complexity of robots consists of a network of interconnected, distributed and sometimes invisible sensor and actuator systems (including mobile phones or appliances). This means that individual devices functioning as machines can cooperate as a network to manipulate or achieve goals (by manipulating energy flows as smart grids do) autonomously as a robot system. With the continuous evolution within the field of Robotic Research, new technical capabilities (modularity, lightweight concepts, wearable robot technology, and social robot technology) have been explored and combined with existing manipulation oriented automation, and robot technology. Over time, the ability of robot systems has grown, allowing them to work more and more in comparably unstructured environments, to those in which human beings operate. This evolution leads to the fact that robot technology, apart from the classical manufacturing industries, can now be introduced and be deployed in numerous fields, such as aircraft production, farming, the construction industry and health care sector. In short, it can be said that automation and robot technology is becoming increasingly ubiquitous, and that it starts pervading our life on earth and in particular built environments. Table 1 lists thematic fields (and Figure 12 visualizes them accordingly) into which automation and robotics is currently advancing as well as approaches and systems within those fields (for further information, see also [2]). It shows that nearly all field of professional and private life are subject to the pervasion of robot technology. Since this pervasion in most cases is linked strongly to the built environment, the list also outlines potential future activity fields for CA.

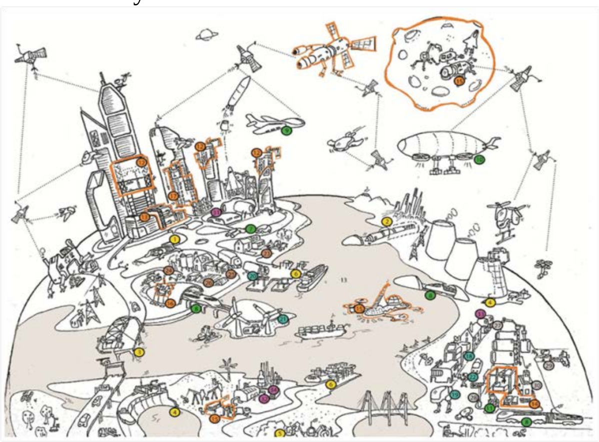

Figure 12. Automation and robot technology becomes ubiquitous and pervades our life on earth. [2].

Table 1 Thematic fields into which automation and robotics is currently advances [2]

Thematic Field		Systems and Approaches
Automated/ Robotic Infrastructure Production	1	Automated road construction
	2	Automated tunnelling (i.e. by TBMs)
	3	Automated bridge construction
	4	Automated con- and deconstruction of dams, power plants, etc.
	5	Automated mining
	6	Automated container port
Automated/ Robotic Transportation Systems	7	Autonomous cars
	8	Autonomous public transport (U-Bahn, Train, etc.)
	9	Autonomous air travel
	10	Automated logistics
	11	Advanced micro-mobility (i.e. Cyberdyne's HAL or Toyota's i-Real)
Automated/ Robotic Construction	12	Automated construction of vertically oriented buildings
	13	Automated construction of horizontally oriented buildings
	14	Housing production
	15	Novel construction Markets accessible through automated/robotic construction: Construction in Space, Sea and Deep Sea, Desert, Arctic areas, etc.)
	16	Automated Building Servicing and Maintenance
	17	Automated De-construction and re-customization
Automated/Robotic Environments	18	Home & Office Automation
	19	Assistance Technologies and Human-Ambient-Technologies
	20	Networked Production Facilities and Supply Networks
	21	Intelligent Energy Generation and Distribution
	22	Service and household robotics
Automated/ Robotic Farming and Food Production	23	Computer Aided/ Robotic Farming
	24	Robotic Milking Stanchions
	25	Automated Food Production Facilities
	26	Customized Food
Automated Robotic Town Management	27	Smart Grids
	28	Automated/ Robotic Traffic Control
	29	Automated/ Robotic Infrastructure Inspection and Maintenance
	30	Automated Supply Management (water, gas, goods, food, etc.)
General Manufacturing Industry	31	Digital/ Cognitive Factories
	32	Mass Customization
	33	Mini Factories, Cloud Manufacturing
	34	Cellular Logistics

8 Conclusions

The existing problems and defects of the construction sector can be successfully addressed by future CA. An overlay of S-curves [32] can be used to describe the relation between the stagnation and technical limits of one technology (conventional construction, section 1) and the initiation, development and growth of new strategies and technologies (future CA), which are at the beginning inferior to the existing technology but gain in importance, performance, and adoption rate over time (Figure 13, [2]).

Conventional construction gives birth to new technologies, which at the beginning phase—where we presently find ourselves (see also section 4)—are inferior in performance due to technical, organizational, and economical obstacles as well as to limited integration within an economic environment still dominated by mature and conventional technology. However, predictions based on analyses of current trends demonstrate that new technologies will outperform the conventional ones over time. Currently, it can already be observed that CA technology, STCR (Single Task Construction Robots) approaches, service robot systems and other microsystems technology are merging with the built environment, becoming inherent elements of buildings, building components, and building furniture. Over time, the ability of robot systems has grown, allowing them to work more and more in comparably unstructured environments as well as to be deployed in numerous and diverse fields. Robot technology becomes ubiquitous, and starts pervading life and built environments. Since this diffusion of robot technology is in most cases strongly linked to the built environment, future activity fields for CA will derive from this.

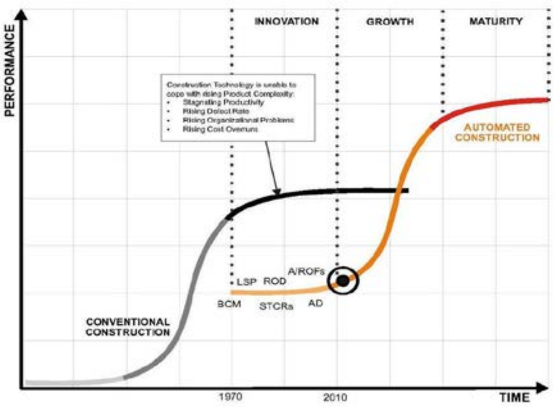

Figure 13. Foster's (1986) S-curves applied to construction. [2]

Acknowledgements

Part of the work described in this article was financed by the German Federal Ministry of Education and Research (GEWOS, BMBF grant number: 16 SV 3970–3976, USA², BMBF grant number: 16SV6191) and the Province of Bolzano (LISA, grant number: Dekret des Landesrates Nr. 22/I-II, 01.06.2010). The article comprises an invited contribution to this Special Issue of the Journal of Automation in Construction based on an extended version of the Keynote entitled "Ki-NEW-matics" given by Prof. Thomas Bock, in the 31st International Symposium on Automation and Robotics in Construction and Mining (ISARC), Sydney, 9-11 July, 2014. Parts of the article (in particular Sections 1-5, 7, 8) are summarizations of concepts and technologies presented in "The Cambridge Handbooks in Construction Robotics", and the Dissertations of Bock (1989) and Linner (2013). Section 6 presents an overview over recent, ongoing work that was/is conducted by the author jointly with Dr.-Ing. C. Georgoulas, M. Eng. J. Güttler and Dr.-Ing. T. Linner, M. Sc. W. Pan, M.Sc. D. Bassily, M. Sc. B. Georgescu, M. Sc. A. Liu Cheng, at the Chair of Building Realization and Robotics.

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