Construction Automation and Robotics for Concrete Construction: Case Studies on Research, Development, and Innovations

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Abstract –

The construction industry, supported by the materials industry, is a major user of natural resources. Automation and robotics have the potential to play a key role in the development of circular construction by increasing productivity, reducing waste, increasing safety, and mitigating labor shortages. Starting with a brief synopsis of the history of construction robotics and the concept of robot-oriented design, this article presents exemplary case studies of research projects and entrepreneurial activities in which the authors have participated that have contributed to the advancement of concrete construction. The activities of the authors have systematically led to spin-offs and start-ups, especially in recent years (e.g., CREDO Robotics GmbH, ARE23 GmbH, KEWAZO GmbH, ExlenTec Robotics GmbH, etc.), which shows that the use of construction robots is becoming an important part of the construction industry. With the use of automation and robotics in the built environment especially for concrete construction, current challenges such as the housing shortage can be addressed using the leading machinery and robot technology in Germany and other parts of the world. The knowledge and know-hows gained in these endeavors will lay the groundwork for the next frontier of construction robotics beyond the construction sites.

Keywords –

Automated Construction Machinery; Concrete Construction; Construction Robots; Infrastructure; Robot-Oriented Design

1 Background

The construction industry, along with the materials production sectors supporting it, is one of the largest exploiters of natural resources on the global stage, both in physical and biological manners [1]. As the need of public housing due to the population explosion is continuously increasing [2], the material and labor costs are rising. The increased competition and shrinking profit margins are some further challenges facing the construction industry. According to McKinsey Global Institute, the construction industry has an intractable productivity problem. Furthermore, the report confirms that while sectors such as retail and manufacturing have reinvented themselves, construction seems stuck in a time warp. Global labor-productivity growth in construction has averaged only 1% a year over the past two decades, compared with growth of 2.8% for the total world economy and 3.6% in manufacturing [3]. Therefore, using innovative solutions to increase the productivity of the construction sector becomes critical to the sustainability of the construction industry.

Furthermore, the construction sector is responsible for 36% of the energy use and for producing 39% of the global carbon dioxide (CO2) emissions including operational energy emissions and embodied emissions that are resulted from materials and construction processes along the whole life cycle [4]. Take concrete as an example: Invented more than 200 years ago, cement concrete continues to be the most frequently used building material. Its usage globally (in tonnage) is twice that of steel, wood, plastics, and aluminum combined [5]. The ready-mix concrete industry, the largest segment of the concrete market, is projected to surpass $600 billion in revenue by 2025 [6]. In addition, concrete production uses substantial amount of energy and raw materials, which results in a large amount of total CO2 emissions (around 7.0%) into the environment [7]. Lacking the use of recyclable materials, the construction sector is generating high levels of waste all around the world.

More importantly, labor safety in the construction sector is a major issue facing the industry today. The reduction in the number of onsite construction workers at height, through applying construction robots, can substantially reduce the chance of fatal accidents and other injuries on the construction sites. According to Eurostat, there were 3552 fatal accidents at work in EU-28 states during 2017, of which one fifth happened in the construction sector [8]. In other words, more than 700 accidental deaths took place within the construction industry in EU countries just in 2017. Accordingly, many of these accidents are directly or indirectly related to concrete construction. The reduction in the number of onsite construction workers at height, through applying advanced technologies, can substantially reduce the chance of fatal accidents and other injuries on the construction sites.

In addition, as the global population is continuously aging, the construction industry is expected to bear the brunt for the years to come. In fact, many countries and regions have already experienced labor shortages in the construction sector, especially high-skilled ones [9-11]. The fact that the construction industry suffers from a bad public image (also known as “3D”: dangerous, dirty, difficult) also aggravates these shortages due to its lack of ability to attract younger workforce. Apparently, novel solutions are needed to mitigate these shortages.

Therefore, improving productivity, reducing waste, enhancing safety, as well as mitigating labor shortages in concrete construction will contribute significantly to the sustainable development of the construction sector, and automation and robotics can play a significant role in this process, just as it already did in the manufacturing industry. This paper will introduce the brief history of construction robotics and present exemplary case studies of research projects and entrepreneurial activities in which the authors have participated that have contributed to the sustainability of concrete construction.

2 The rise of construction robotics

The construction automation and robotics is a new yet flourishing research topic. Ever since the first stationary construction robotics’ debut in the 1960s in Japanese modular prefabrication of the Sekisui Heim M1 that was designed by Dr. K. Ohno (see Figure 1), then from the late 1970s the first on-site construction robots (see Figure 2) were developed by Japanese general contractor Shimizu Corporation due to the lack of skilled labor, low construction quality, and bad public image, about 50 construction robot systems have been developed in the 1980s. Other catalysts also include high land prices, high interest rates, and high living cost which required rapid, on-time, high quality construction project delivery on site as planned as well as immediate return on investment. As a result, from the 1990s, on automated construction sites (e.g., the pioneering SMART System developed by Shimizu Corporation in 1992, see Figure 3) have also become a worldwide research topic [12].

Figure 1. Stationary construction robotics of the Misawa-Toyota Homes assembly line (photo: T. Bock)

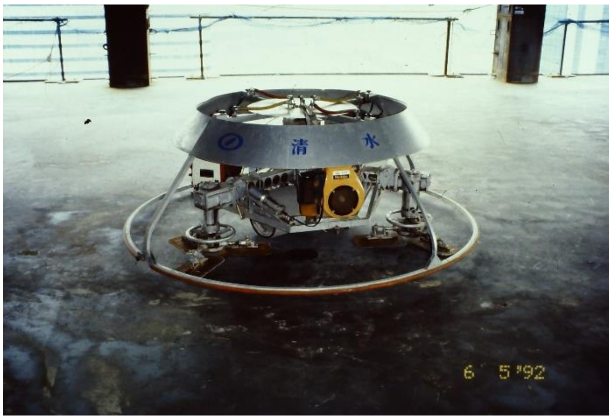

Figure 2. Concrete leveling robot developed by Shimizu Corporation (photo: T. Bock)

Figure 3. The pioneering automated construction site “SMART” developed by Shimizu Corporation (photo: T. Bock)

Further innovation push was triggered by earthquakes, landslides, volcano eruptions, and tsunamis where initially since 2000s, teleoperated construction robots (see Figure 4) and since 2010s, autonomous scrapers, graders, rollers, compactors, trucks, and excavator fleets for large infrastructure projects such as dams, roads, bridges and tunnels have been developed and applied (see Figure 5). For maintenance, inspection, and repair of buildings and infrastructure such as tunnels, roads, dams, and power plants, various maintenance robots were developed (see Figure 6). Most of these solutions are directly or indirectly related to cement or concrete construction.

Figure 4. Teleoperated construction robot for concrete tunnel construction (photo: T. Bock)

Figure 5. Autonomous heavy machinery fleet for large infrastructure projects (Photo: T. Bock)

Figure 6. Maintenance robot Enryu T-53 developed by TMSUK Co. Ltd. (photo: T. Bock)

As a national project on concrete construction, the Solid Material Assembly System (SMAS, see Figure 7) based on an earthquake-proof reinforced concrete block assembly and disassembly robot was successfully developed and tested at the Building Research Establishment (BRE) of Japan's Ministry of Construction from 1984 to 1988. During the project, the co-author T. Bock developed the notion of Robot-Oriented Design (ROD) [13], which was applied to the first automated construction site SMART (Figure 3) and to Obayashi's Automated Building Construction System (ABCS) from 1992 onwards, and also laid the foundation for the development of many construction robot systems.

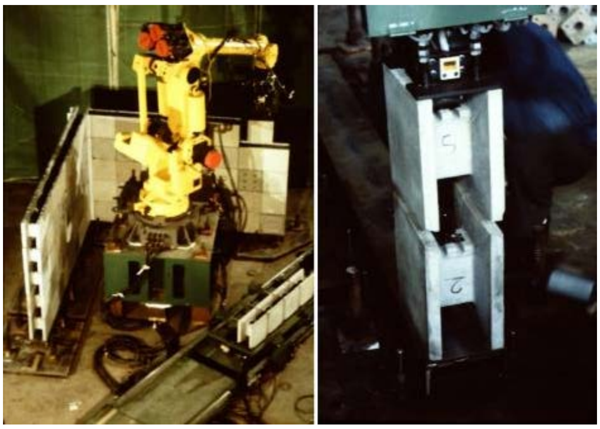

Figure 7. The SMAS robot developed for the assembly and disassembly of reinforced concrete blocks using ROD concept (photo: T. Bock)

3 Case studies on the concrete processing construction robots developed by the authors' team

As mentioned above, construction robots are robots or automated devices that are developed primarily for tasks on the construction sites. It is a highly cross-disciplinary field which requires an integration of a variety of knowledge and expertise such as civil engineering, architecture, industrial design, construction management, robotics, mechanical engineering, electrical engineering, and informatics. Today, the application fields of construction robotics continue to expand. Bock and Linner summarized 200 existing construction robot systems into 24 categories based on their functions, many of which are directly or indirectly related to cement or concrete construction [14]. However, there is still a gap in the ubiquitous application of concrete processing robots due to various reasons, such as insufficient evidence of net economic benefits, lack of modularity and flexibility, lack of skilled labor for operation, incompatibility with other construction tasks, and time-consuming onsite setup [14]. Therefore, in the following sections, three exemplary case studies will be introduced on how Prof. Thomas Bock and his team attempted to bridge the gap in the field of concrete construction using construction robotics in a global context in recent years.

The endeavors in Europe began in the early 1990s. After the German reunification, there was an increased need for construction, especially for affordable housing - as is the case today. Together with SÜBA Bau AG, T. Bock developed the production system for the "x8 Haus" (see Figure 8) as part of his professorship for automation in construction operations at the civil engineering faculty of University of Karlsruhe (now Karlsruhe Institute of Technology) in 1990. It offered 100 m^2 of living space on two stories with a bathroom-toilet building service module, without a basement and can be prefabricated in 8 days by a specially developed multifunctional system with portal robots, assembled on site in 8 hours and sold for 80,000 German Marks (see Figure 9).

Since then, over the past three decades, T. Bock and his team from the Chair of Building Realization and Robotics at Technical University of Munich along with their start-ups and spin-offs such as CREDO Robotics GmbH, ARE23 GmbH, KEWAZO GmbH, ExlenTec Robotics GmbH have vigorously contributed to the automation and robotization of construction especially regarding concrete with several research and innovation projects in different regions around the world.

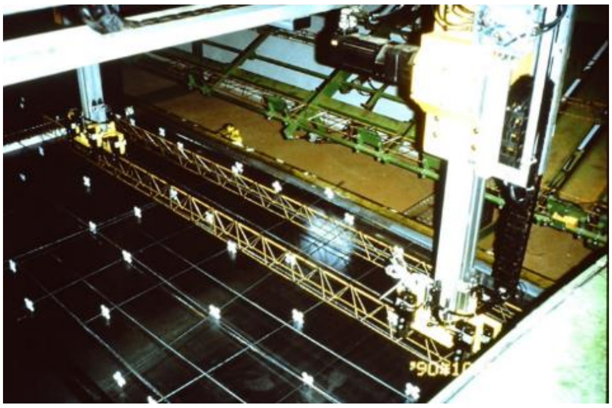

Figure 8. Robotic reinforced concrete parts production system for "x8 Haus" (Photo: T. Bock)

Figure 9. The built "x8 Haus" applying the ROD concept (Photo: T. Bock)

3.1 Case study 1: Consultancy on Investigating the Potential of Implementing Robotics and Automation in the Context of Large-scale Housing Development for Hong Kong SAR

The public housing construction industry in Hong Kong, predominantly using prefabricated concrete as the construction material, faces conspicuous challenges of high demands, safety, an ageing workforce, inconsistent quality and stagnant productivity. The consultancy project commissioned by the Construction Industry Council (CIC) of Hong Kong SAR evaluates the current on-site construction operation and identifies the existing bottlenecks that can be enhanced by implementing robotics and automation. In the current housing construction field, the systematic and scientific method to approach this type of undertaking, especially when closely associated with the industry and authorities, has not been comprehensively discussed.

Therefore, this project highlights the activities that signify these objectives using systems engineering, which include five key activities: literature review, industry survey, on-site case study, co-creation workshops, and potential pilot project. As a result, a range of robotic applications that are tailor-made for Hong Kong's prefabricated public housing industry are recommended and hierarchically categorized [15]. In addition, as one of the most needed robotic applications, a semi-functional prototype of multifunctional façade-processing robot using specially-designed cartesian kinematics (e.g., painting, cleaning, grinding, inspection, marking, etc.) was designed, built and tested in laboratory as a proof of concept (see Figure 10 and Figure 11). The robot can work on the concrete façade of high-rise public housing buildings in Hong Kong and beyond in collaboration with workers. In summary, the above-mentioned learnings gained from this study will inspire the construction industry to initiate and explore innovative, compatible as well as feasible solutions to the implementation of the robotic application in specific regions in the world in the future [16].

Figure 10. The multifunctional façade-processing robot showcasing the painting function on the façade of public housing buildings in Hong Kong (image: R. Hu)

Figure 11. The semi-functional prototype of the multifunctional façade-processing robot exhibited in the Construction Innovation and Technology Application Centre in Hong Kong (photo: R. Hu)

3.2 Case study 2: HEPHAESTUS cable-driven façade installation robot in concrete structures

HEPHAESTUS stands for Highly Automated Physical Achievements and Performances Using Cable Robots Unique Systems. The HEPHAESTUS project explores the innovative use of robots and autonomous systems in construction, a field where the incidence of such technologies is minor to non-existent. The project aims to increase market readiness and acceptance of key developments in cable robots and curtain walls. The installation of curtain wall modules (CWMs) is a risky activity carried out in the heights and often under unfavorable weather conditions. CWMs are heavy prefabricated walls that are lifted normally with bindings and cranes. High stability is needed while positioning in order not to damage the fragile CWMs. Moreover, this activity requires high precision while positioning brackets, the modules, and for that reason, intensive survey and marking are necessary. In order to avoid such inconveniences, there were experiences to install façade modules in automatic mode using robotic devices.

In HEPHAESTUS, a novel system has been developed in order to install CWMs automatically. The system consists of two sub-systems: a cable driven parallel robot (CDPR, see Figure 12) and a set of robotic tools named as Modular End Effector (MEE, see Figure 13). The platform of the CDPR hosts the MEE. This MEE performs the necessary tasks of installing the curtain wall modules. There are two main tasks that the CDPR and MEE need to achieve: first is the fixation of the brackets onto the concrete slab, and second is the picking and placing of the CWMs onto the brackets. The first integration of the aforementioned system was carried out in a controlled environment that resembled a building structure. The results of this first test show that there are only minor deviations when positioning the CDPR platform [17]. In future steps, the deviations will be compensated by the tools of the MEE and the installation of the CWM will be carried out with the required accuracy automatically, which will be reported in upcoming publications.

Nevertheless, the initial on-site test results suggest that the robot can potentially boost productivity by 220% for an average construction job, compared to the conventional façade installation method. Furthermore, a study on the cost-benefit analysis (CBA) of construction robots estimates that the HEPHAESTUS cable-driven robot for facade installation is theoretically worth investing in in the UK, as well as in the majority of G20 countries [18].

Figure 12. The HEPHAESTUS cable-driven façade installation robot on a testing site (photo: K. Iturralde)

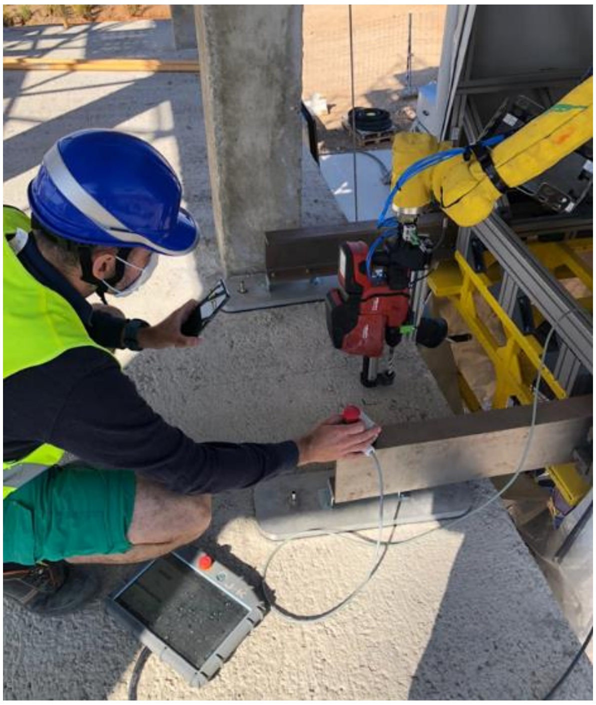

Figure 13. Co-author K. Iturralde checking the performance of the modular end-effector of the HEPHAESTUS robot (photo: S. Palencia Ludeña)

3.3 Case study 3: ARE23 wall painting robot

ARE23 GmbH was co-founded in 2020 in Germany, and the CEO, Dr.-Ing. Wen Pan is a researcher at the Chair of Building Realization and Robotics. It is an augmented robotics engineering company whose mission is to support laborers in the construction sector with artificial intelligence (AI) and robotics-driven technology. It automates the concrete coating industry and digitalizes the entire operational process with affordable solutions. Its products including small and large-scale spray coating robots for residential and commercial-sized projects complement human skills, improve productivity, and cuts costs.

Providing the workforce with a catalogue of robotic spraying solutions will allow the industry to satisfy the increasingly growing labor demand while guaranteeing premium paint application quality. A 3-axis machine for an interior surface coating robot that can autonomously scan a surface, determine its optimal path, and spray hard to-reach surfaces. Leveraging Vention's cloud-9 programming environment, they were able to write their own code and quickly merge it with their in-house operating system (ARE-OS). Next, the start-up aims at developing a range of robotic solutions for the painting, plastering and coating of the built environment.

For example, the "TITAN" range (Figure 14) is developed for larger commercial and industrial scenarios, while the "COMPACT" range (Figure 15) is suitable for residential, hotels, and offices. The initial test results suggest that both variants of the robot can potentially boost productivity by 250% compared to the conventional manual wall spraying method, with the same number of operators involved in both methods. The fully functional "COMPACT" product will be ready for the commercial pilot in Germany in early 2023. Although the technologies developed by ARE23 GmbH were primarily customized for the German market, their modularity and affordability ensure that they can be easily adapted for other regions in the world as well.

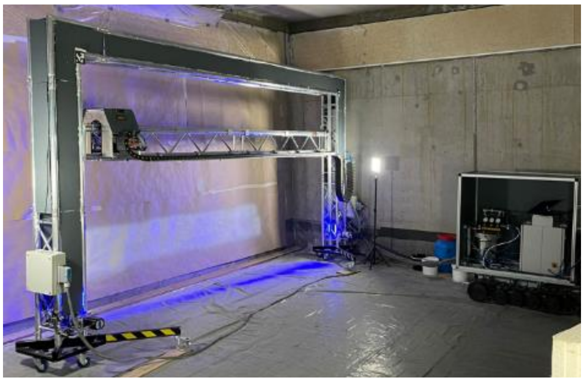

Figure 14. Prototype of the "TITAN" range on a pilot project (photo: ARE23 GmbH)

Figure 15. Proof-of-concept prototype of the "COMPACT" range (photo: ARE23 GmbH)

4 Conclusion

In summary, construction automation and robotics can potentially play a significant role in the sustainable development of the concrete construction industry by improving productivity, reducing waste, enhancing safety, as well as mitigating labor shortages. The research and innovation endeavors represented by several research projects and entrepreneur activities conducted by the Chair of Building Realization and Robotics at Technical University of Munich along with their in-house spin-offs and start-ups such as CREDO Robotics GmbH, ARE23 GmbH, KEWAZO GmbH, ExlenTec Robotics GmbH over the years have contributed significantly to the knowledge and know-hows in the construction industry, especially in the concrete construction sector.

In connection with new approaches from the field of human-centric use of robots, human labor can be perfectly supplemented in order to compensate for the shortage of skilled workers. Automated construction machinery for infrastructure construction offers highly efficient solutions for the expansion and renovation of roads, railroads, bridges, and tunnels. Advances in the field of digital connection and programming of robots increasingly facilitate the use of these solutions. Future research will be conducted on the universal simulation environment for customized robotic applications for a resource-efficient and human-centric construction industry. Furthermore, the knowledge and know-hows gained in these endeavors will lay the groundwork for the next frontier of construction robotics beyond the construction sites, such as dismantling concrete buildings and infrastructure (Figure 16) and constructing space architecture (Figure 17).

Figure 16. Concrete dismantling and concrete recycling robot Garapagos (Photo: T. Bock)

Figure 17. Next frontier for construction robotics: space stations and colonies (Photo: T. Bock)

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