Construction Robotics: Current Approaches, Future Prospects

Alberto Balzan

Claudia Cabrera Aparicio

Dario Trabucco

Authors

Alberto Balzan, Research Assistant
Claudia Cabrera Aparicio, Research Assistant
Dario Trabucco, Research Manager
Council on Tall Buildings and Urban Habitat
Research Office, Iuav University of Venice
Dorsoduro 2206
Venice, 30123
Italy
t: +39 041 257 1276
e: dtrabucco@ctbuh.org
CTBUH.org

Alberto Balzan is a licensed architect who graduated with honors from the Università Iuav di Venezia in 2017, after a study experience at the Illinois Institute of Technology (IIT) in Chicago. His thesis was focused on the potentialities of smart dynamic façades. Passionate about technology and innovation, Balzan is currently working for the CTBUH Research Office at the Università Iuav di Venezia, where he is also teaching-collaborator of Professor Dario Trabucco on the courses of Building Elements and Architectural Technology.

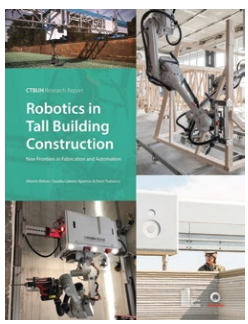
Claudia Cabrera Aparicio is an architect and research assistant at the CTBUH Research Office at the Iuav University in Venice. She received her Bachelor and Master's in Architecture degrees from the Polytechnic University of Madrid, School of Architecture (ETSAM) in 2018, and studied under exchange programs and scholarships, at the Academy of Fine Arts, Vienna in 2015, and at the Illinois Institute of Technology (IIT), Chicago from 2015–2016.

Dario Trabucco, PhD, is CTBUH Research Manager and researcher at the IUAV University of Venice, Italy. He is involved in teaching and research activities related to tall buildings, including the LCA analysis of tall buildings, service core design and issues pertaining to the renovation/refurbishment of tall buildings. In 2009 he obtained a PhD in building technology with a thesis entitled "The Strategic Role of the Service Core in the Energy Balance of a Tall Building."

Abstract

In recent years, robotics has entered strongly in a large number of industrial sectors, especially the automotive, manufacturing, aeronautical and agriculture sectors, having a major impact on industrial, labor and technological policies, as well as within the development dynamics of each sector's products. The construction sector is one of the largest global industries, but it is still considered a low-tech and disjointed environment. It is clear that the new phase of construction robotics now dawning defies conventional interpretations and comparisons to similar industries. A reshaping and clarification of concepts, incorporating a much more flexible understanding of the term "robot", as well as a clear classification and formulation of its future potential, is a crucial step to responding to current innovations and adapting them to the construction sector's needs. The research underlying this paper seeks to provide an extensive framework of the relationship between the building and robotic industries, as well as to investigate the possible role of robotics in the improvement of the building sector in the near future.

Keywords: Construction, Robotics



Schindler

This paper summarizes the results of the CTBUH Research project *Robotics in Construction*, kindly sponsored by Schindler. The full results can be found in the CTBUH Research Report: *Robotics in Tall Building Construction: New Frontiers in Fabrication and Automation*.

See advertisement on page 39 for details.

Approaches to Robotic Technologies in the Building Industry

Robotization of Traditional Construction Procedures

Two main tendencies regarding the approach to robotics in construction were explored, through different stages of development and adoption by the sector, following diverse rationales. There is a more "classical" interpretation of "robotization" of conventional construction procedures, whose principle is to execute traditional construction operations with robotic mechanisms (see Figure 1). These devices perform the same tasks as human workers, either replacing or complementing them in the performance of dull and physically demanding activities. Within this framework, the trend for the first line of development has shifted from a first stage, in which the objective was merely the repetition of construction-related tasks, to the current trend of pursuing the manufacturing of devices with an ever-increasing level of self-sufficiency. These devices are able to collect and process data in order to increase their adaptability to the context within which they operate, and are thus able to operate uninterrupted. For collaborative robots, intended to work alongside human workers, the required degree of sophistication is related not so much to self-sufficiency as to safety and

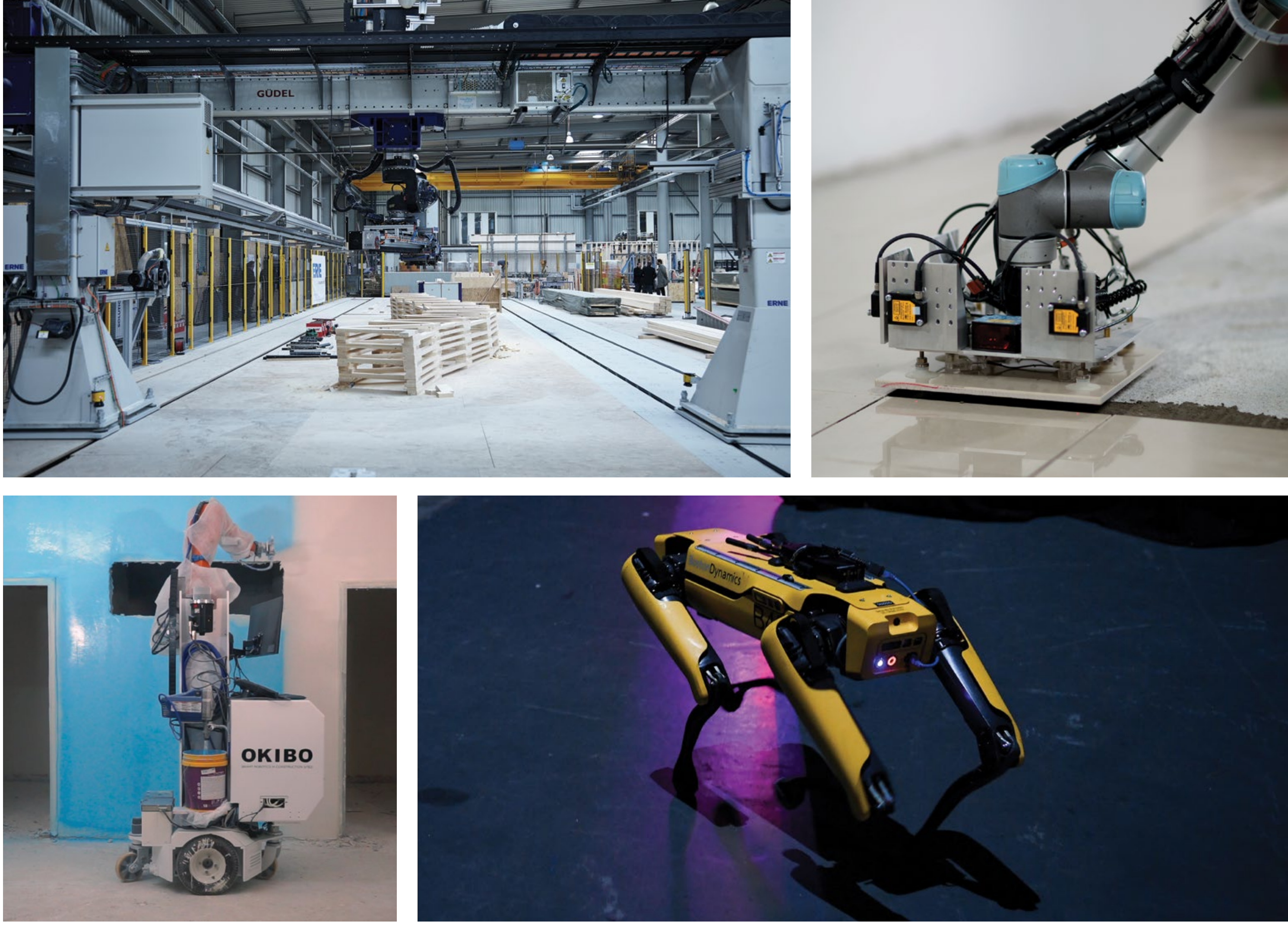


Figure 1. Robotization of traditional construction operations can extend to structural assembly (upper left), repetitive behaviors such as tiling (upper right) and plastering (lower left), and inspection of dangerous or combined environments, one possible use of Spot (lower right). This terrestrial robot has the ability to autonomously navigate its environment, carry inspection equipment, and collect crucial data. © Top left: ETH Zürich; Top right: Gramazio Kohler Research, ETH Zürich; Bottom left: Okibo; Bottom right: Web Summit (cc by-sa)

communication issues surrounding the machine-human interaction. Their effectiveness would, in this case, be enhanced by implementing gestures and natural speech translation mechanisms, for instance.

Digital Fabrication

The second approach is based on the generation of construction processes intended to be carried out by robots exclusively, unlocking new design and building options, conceiving innovative manufacturing techniques, and thus revolutionizing the entire construction industry. Indeed, according to several experts, such as the CEO of Scaled Robotics Stuart Maggs, robots should be exploited to undertake purposes other than traditional building operations based on human capacities (Davies, et al. 2019). In this line of thought, robots should avoid imitating conventional tasks, as well as the use of tools and materials that have been developed and adapted for human operation.

As argued by Prof. Fabio Gramazio of ETH Zürich (F. Gramazio, personal communication, 6 May, 2020), such a new commitment would not seek to improve the construction industry by reducing costs, but rather becomes strictly related to creating new architectural typologies and supporting sustainability. In this framework, the novel approach would be intended to solve the problem of increased costs implied in the realization of optimized architecture. Shajay Bhooshan, senior associate at Zaha Hadid Architects and co-founder of CODE, the computational design research group, affirms that the multidisciplinary opportunities granted by digital fabrication processes allow the realization of high-performing structures with complex, optimized geometries driven by material savings, as well as improved structural efficiency and environmental performance (Bhooshan, personal communication, 3 April, 2020). Despite the lack of practical examples of digital fabrication applications in complex architectural projects, several pavilions and installations have been designed and built, demonstrating the potential of such digital processes (see Figure 2).

Changes Driven by Robotic Construction

Considerations and Impacts on Building-Related Professions

Opinions diverge on the future of robotics in relation to its impact on jobs, accentuated by the recent inclusion of digital fabrication processes into building sites. The International Federation of Robotics (IFR) argues that processes have been automated for centuries (i.e., the introduction of self-driven machines or advanced grain mills), changes have been absorbed and jobs have evolved, which is not to say the fear of workers being replaced and certain professions' extinction is unjustified (IFR 2018). These occupations have undergone different transformations; some have indeed

Figure 2. The additive process of filament winding, using tensioned fibers and resin, is seen at the BUGA Fibre Pavilion at the Institute for Computational Design and Construction at the University of Stuttgart.

disappeared, but some have been transformed, while others have been created to incorporate new automated mechanisms, generating great demand. For example, following the mass adoption of networked office computing, one of the key competencies of the administrative assistant has transformed from managing tasks to managing computing systems.

IFR sets a series of possible future impacts on employment related to widespread implementation of robots in the working environment (IFR 2017). The organization submits that automation is responsible for generating new business models (IFR 2018), linked both to providing new goods and services, and helping existing companies to absorb the required changes in order to compete in the construction market, improving in terms of efficiency and flexibility, as well as making companies, and by extension, nations more competitive. Along this line, Bessen (2016) observes that automation does not necessarily imply job disappearance, considering that either "greater productivity might reduce prices and thus increase product demand, offsetting the labor-saving effect" or "increasing the productivity of one occupation might induce a substitution with other occupations; work may be transferred to the newly more productive occupation," except in the case of an inelastic employment demand, which would imply job losses.

On this topic, it is interesting to elaborate a distinction: "jobs" are not the same as "activities." IFR sustains that "robots substitute labor activities, but do not replace jobs," and robots' activities will complement and assist human workers, resulting in a positive net impact (IFR 2017). Various researchers acknowledge that, by 2057, almost half of current construction jobs could be substituted by robots (Belton 2018).

On the other hand, supporters of incorporating robots into work sites pinpoint that only a few medium- and low-skilled jobs would be replaced, while the spectrum of high-skilled workers will expand, with many becoming robot operators. Many experts concur that medium-skilled workers would be largely replaced by robots, and thus require training to gain further knowledge and competencies to guarantee the preservation of jobs in a new, highly technological work environment, going from performing repetitive tasks to monitoring robots that perform those tasks instead (IFR 2017).

When machines are understood as "capital," human factory workers correspondingly become "cost and error factors" in the process, and operators are economically cheap and unskilled. Many experts in the field understand introducing technological processes and machines into the building environment to be a technological reinterpretation of "craftsmanship," and believe that new approaches to robotics in the industry will lead to new conceptions of the "construction worker" (see Figure 3). This theory introduces the idea of craftsmen controlling the entire production process, not only a part of it; it makes reference to pre-Industrial Revolution artisan professions, and gives a sense of autonomy to the process and expertise to the performance of functions. For instance, Gramazio (2020) asserts that robots and humans exclude each other in the race for automation because of historic conceptions of automation and human labor. Gramazio posits the "digital craftsman," a concept that already exists in a large number of companies dedicated to digitally producing parts and assembling them. This would involve a team of machines and skilled human operators, who are experts in the interdisciplinarity between the robotic and digital worlds, and the physical and material domains. This generates an efficient and collaborative workflow between human and machine, and entails a complete shift of the construction site and stakeholders, which does not preclude a combined effort with traditional manual labor. In any event, the relative immaturity of digital fabrication, together with the intrinsic complexity of the technologies, activities implied, and the outcomes themselves, usually require a more extensive human-robot collaboration.

With all this in mind, is reallocation or upskilling of human labor a real possibility? One must consider that not all people have the aspiration of becoming IT experts or are capable of performing highly qualified jobs; such people will be unemployed if robots occupy their jobs. And it is important to note that, in the last instance, humans need to work, and an occupation is required to live,

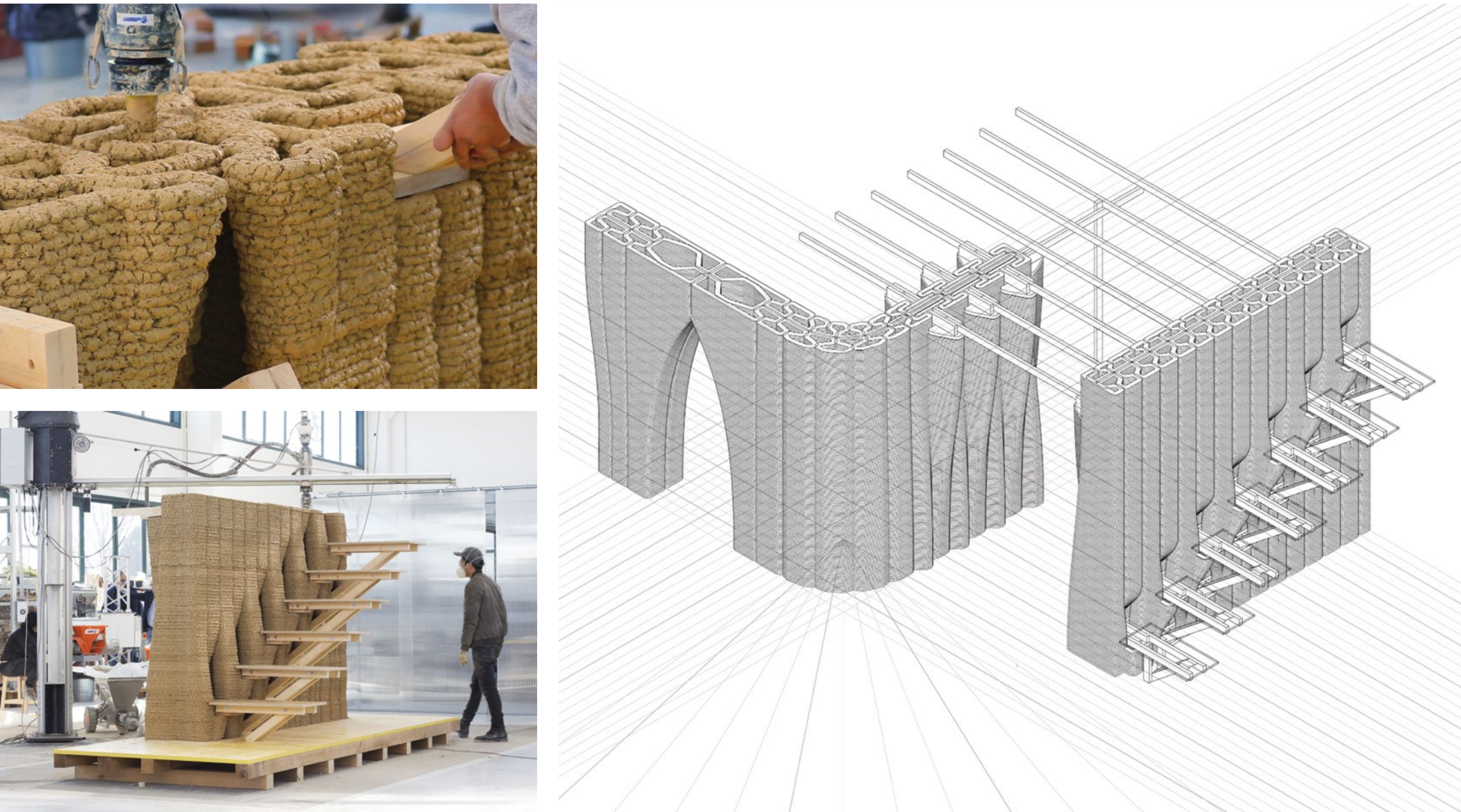


Figure 3. If humans think of themselves as "digital craftspeople" controlling the entire design and production process, new roles for human labor and new kinds of robotically produced structures could arise. © WASP

> "By 2026, the digitalization of non-residential construction is expected to result in worldwide annual cost savings of 10 to 21 percent."

Figure 4. The FieldPrinter, developed by Dusty Robotics, achieves robotic layout automation, bringing BIM data onto the construction site. © Dusty Robotics

as work dignifies humanity. In this regard, several politicians and tech industry leaders, such as Microsoft co-founder Bill Gates, have proposed the institution of a tax dedicated to subsidizing people whose jobs have been substituted by robots, and to promote a gradual and smooth transition to automation (Waters 2017). On the contrary, IFR believes the introduction of a "robot tax" is no guarantee of a social welfare state, but is instead a deterrence to robotic investment (IFR 2017). In any case, most agree on the fact that governments need to work on coverage of social payments out of revenue generation.

Influence of Further Complementary Technologies

The communication fragmentation within the building process, from the first stages to the last construction phase, is a drawback. Results from a survey conducted by CTBUH on 1 July 2020, involving experts in related fields, show that the potential for automation to drive innovation and productivity in the construction field will be highly dependent on the future integration of information from multiple construction stages, through the implementation of a continuing process. Efficient information exchange enhances accuracy and real-time decision-making, along with reductions of delivery times and material losses, as a result of the decrease of inconsistencies in the final stages of the construction process. Moreover, by 2026 the digitalization of non-residential construction is expected to result in worldwide annual cost savings of 10 to 21 percent, across diverse stages of a project (Castagnino et al. 2016), which would result in a reduction in the cost of robots.

The implementation of building information modeling (BIM) methodologies and new software applications call for the integration of robotic systems and design software on a central platform, with access to a large database containing construction knowledge (see Figure 4). These technologies are essential for setting early collaboration and coordination between stakeholders, as well as precise information disposal and exchange, and ultimately, to make the investment in new robotic technologies economically and technically sustainable. Besides the incorporation of these technologies, several other complementary innovative mobile and cloud technologies—including digital twin, 5G, Industrial Internet of Things (IIoT), cloud robotics, Big Data, virtual and augmented reality (VR and AR), parametric design, material science, machine vision, machine learning, etc.—can make a substantial difference and help promote the widespread use of robotics in the construction environment (see Figure 5) (CTBUH 2020). At the moment, extended networks and signal repeaters are required in construction works more than 200 meters in height; in this regard, 5G technologies, together with IIoT solutions, enable robot control on high-rise buildings and enhance their autonomy and response speed. This opens up the possibility of working on remote sites without the need for a Wi-Fi base station, as well as improved interconnection between devices in the cloud (Belton 2018), resulting in cloud robotics, the possibility of robots delegating processing activities to remote servers in order to take advantage of their computational power, eliminating the need to install expensive robot hardware and software. Furthermore, managers will be able to monitor and synchronize the activities of numerous IIoT robots across different locations, and devices will issue their own performance statistics and conduct predictive maintenance (Matthews, 2019). Ultimately, artificial intelligence (AI) and derived data analytics can be the final steps to the successful incorporation of robots into building sites (Davies, et al. 2019).

Thoughts on the Successful Deployment of Construction Robots

Drawbacks and Drivers

A confluence of diverse factors has influenced the slow uptake of robotic innovations in the building industry. Besides the intrinsic complexity of the product to be realized, a major concern of construction automation relates to the numerous variables that can affect architectural customization. While almost any industrial product can be standardized, buildings are dissimilar across factors of size, typology, culture, economy, regulations, and other specific requirements. Even in the case of buildings with identical characteristics, there are many other variants and factors that can differentiate them. Therefore, attempting to compare the construction sector with any other industry in connection with this concept, and to apply the same robotization procedures, could possibly lead to failure. This was the case of the miscarriage of Japanese "sky factories" of the 1990s, in which the insufficient technological level of their components at the time resulted in a lack of flexibility of the system to adequately adapt to different building settings.

Another relevant difference between other industries and the building sector is that, in the first, assembly lines are arranged in order for products to move around, and robots remain in a stationary position. In construction, the output (the building) remains still, and robots need to autonomously move, or be manually driven, to diverse locations. Moreover, the environmental conditions of a building site are completely different from those of a factory; the former are unstructured, usually exposed to weather conditions and other continuously changing variables, whereas the latter are structured with a high level of control and planning. These difficulties, together with the high cost of automated devices and alternative robotic processes, the immaturity of certain novel mechanisms, the high upfront investment cost, the lack of fluency in the communication process between various stakeholders, and the need to create new professions and workgroups, are significantly slowing construction robotics' market development. At the same time, these are some of the reasons why the industry has been more inclined towards prefabrication, limiting site operations to assembly tasks, which, in any case, also has important disadvantages, including the pollution generated, and the increasing costs derived from transportation of parts.

As a counterbalance, major motivations pushing the sector forward include the pursuit of increases in safety, speed and precision, and the drive towards sustainability and the rapprochement between robotic processes and personalization; this is supported by the decreasing numbers of skilled traditional construction workers and the aging of the population in most developed countries (see figures 6 through 8).

Fully Automated Construction Sites

There seems to be a broad consensus that robotics will have a central function in the future of the building industry, even though there are different perspectives on how this implementation will take place. Most experts agree that the establishment of full automation of building processes is still far from being achievable (CTBUH 2020). Moreover, some believe that the outcome of automating construction robots to the utmost level is not the optimal solution,

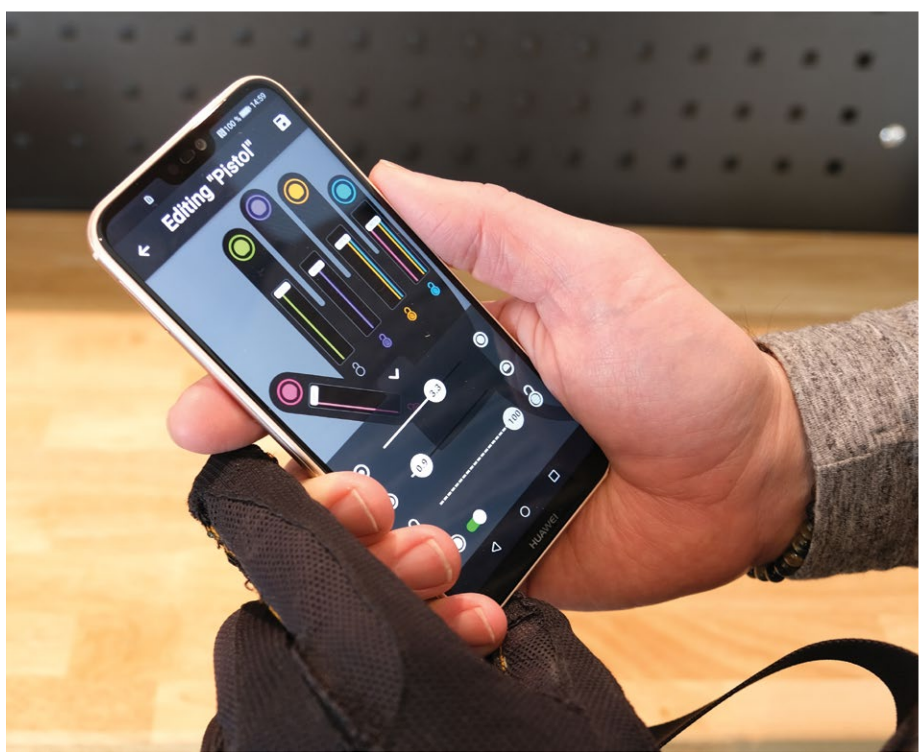


Figure 5. The IronConnect is a digital interface that allows the user to adjust exoskeleton settings, creating a more personalized and comfortable experience, which may help users acclimate to using wearables. © Bioservo

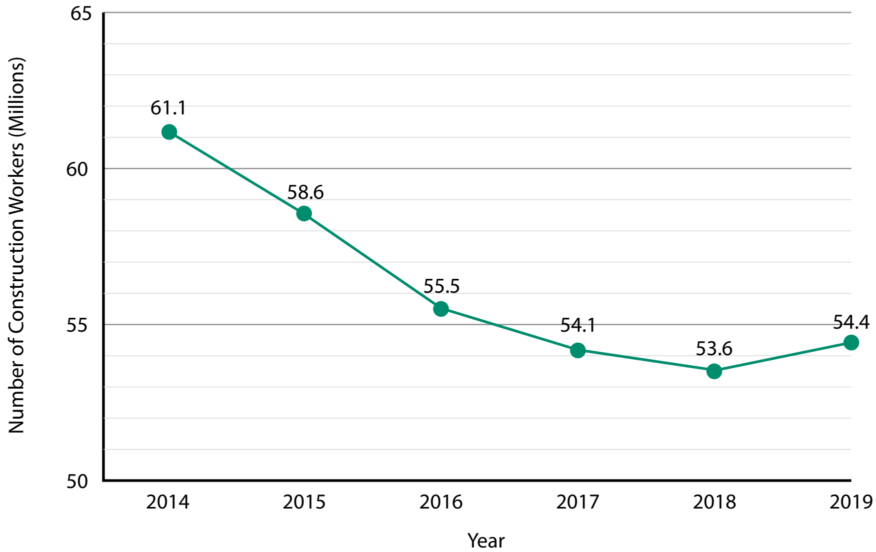


Figure 6. Total number of migrant workers involved in the construction industry in China, 2014–2019. Source: National Bureau of Statistics, compiled and drawn by CTBUH

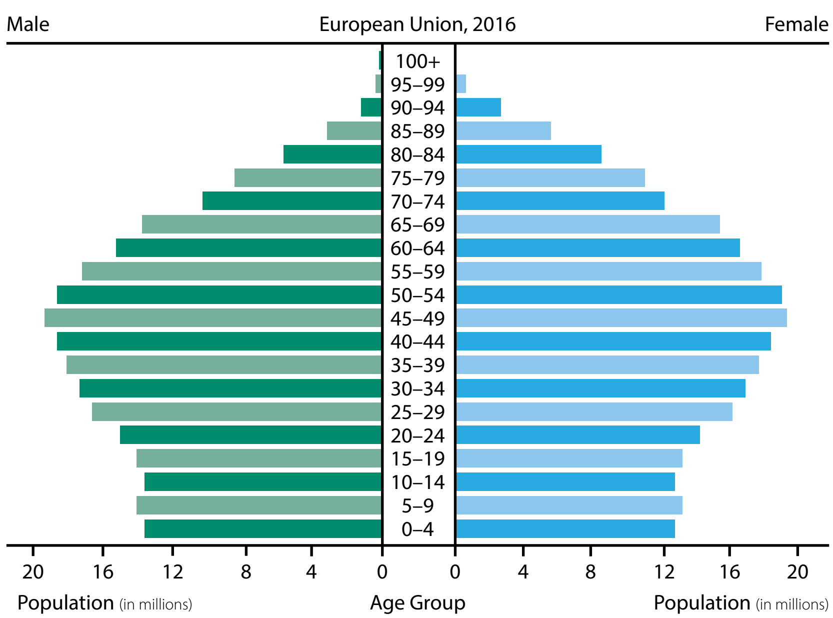


Figure 7. Graph showing Europe's age distribution, in 5-year increments, across gender and population in 2016. The changing shape of the population pyramid indicates that it is skewing older, which may have implications for the future of the construction labor market. Source: CIA, redrawn by CTBUH

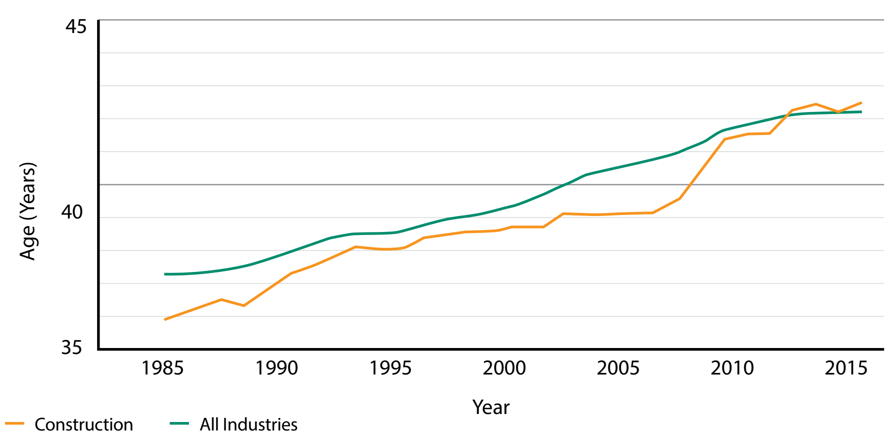


Figure 8. The average age of construction workers in the United States, compared to other industries, 1985–2015. Source: US Bureau of Labor Statistics / CPWR Data Center; redrawn by CTBUH

because costs increase exponentially on the approach to the final stage. On this line of thought, Bharath Sankaran, CTO and co-founder of Scaled Robotics asserts that the level of autonomy and investment required for these devices is such that allowing the robot to substitute for the human workforce is nowhere near to being profitable (personal communication, 17 August 2020). This factor therefore tends to prevent investors from pursuing total automation, and pushes them to instead seek a working environment with a more balanced ratio of human workers and machines, according to Gramazio (2020). It is therefore essential to find a compromise between the inversion and the cost of automating the process and the result achieved. The ideal level of automation would be, according to Sankaran, that which enables the expansion of cost-effective, simpler single-task construction robots (STCRs), developed to be proficient in carrying out a specific task (see Figure 9). In this regard, dangerous, repetitive and remote operations are the most probable to be automated (Davies, et al. 2019); yet human workers will continue to be an essential asset to the construction site for a long time, carrying out more complicated tasks that require specific skills, possibly with the help of augmenting devices and technologies, such as exoskeletons and smart glasses, so that AR can facilitate their work (see Figure 10). Following this lead, and although the market of construction robots reflects a general image of unreadiness due to the lack of maturity of the existing technologies, there are a few devices that show a higher degree of complexity in pursuit of maximum self-sufficiency, such as the elevator installation robot "Schindler R.I.S.E" (see page 22).

On-Site and Off-Site Effective Applications

Another recurrent issue is the presence of robotics in both on-site and off-site domains, about which experts in the field are not always unanimous (CTBUH 2020). The history and literature show that, in relation to traditional robotization procedures, attempts have been made since the 1970s to incorporate, in a straightforward way, these devices into the construction site, though it

Figure 9. These single-task robots, developed by Shimizu in the 1980s, performed activities such as spraying fireproofing on steelwork. © Shimizu Corporation


Figure 10. The Bioservo Ironhand allows workers to exert less grasp/grip strength during repetitive tasks. © Bioservo

has not yet had the expected disruptive impact. On the side of digital fabrication, conversely, robotic processes have thus far been explored off-site, due in part to its incipient nature, and for economic and convenience reasons. Initial testing is being carried out inside workshops, which provide the structured environmental conditions required to experiment and progress rapidly, placing the experimenters in control of all possible variables (see Figure 11). In order to render adequate certain devices to outdoor or unstructured contexts, such as with standard robotic arms, it is necessary to modify or properly equip them. Nevertheless, experiments with on-site applications have already been conducted, inasmuch as the final objective of digital fabrication within the building industry is to be able to construct directly on-site. This avoids the transportation of delicate and cumbersome parts, leaving only raw materials to be transported. In any case, considering that certain digital fabrication processes have been maturing for at least 20 years, experts in the field believe that the exploitation and spread of this approach in on-site applications will happen in the foreseeable future.

One of the most interesting perspectives is the idea of introducing an alternative to the duality on-site versus off-site robotics. The concept is that of "near-site" construction automation, which has already been introduced and versioned by several actors, including MTC's Factory in a Box (FIAB) and Odico's Factory on the Fly (see Figure 12) (Søndergaard, et al. 2020; MTC 2019). It is based on the idea of a small factory cell plugged into the construction site, implying a rapid deployment, remote management and modular manufacturing. Instead of producing the parts and delivering them to the construction site, what is delivered is the machinery required for the manufacture of the components. The interest in these proposals resides in the idea of replicating a factory's stable environmental conditions near-site, producing parts in a more controlled context with minimal error, but maintaining at the same time the convenience of producing the pieces on-the-go, with in-situ corrections, and real-time immediacy, ultimately incorporating the process into the building setting workflow. Moreover, due to the proximity to the construction site, these systems can support local economies, by making use of indigenous materials, expertise and craftsmanship.

A possible future prospect that is being welcomed by the industry and experts, is that of generating synergy by combining in a flexible manner the diverse approaches to robotics in the construction process; this would occur to varying degrees, according to the particular environmental conditions of each building project. In this hybrid scenario, processes stop being exclusive to location (on-, near- or off-site) or actor (robot or human), and the outcome is the result of a combination of varied procedures, each exploiting its potential. This disaggregation of tasks could work in relation to the scale of the project to be addressed; in the case of factory-like off-site and on-site processes, which work best in large-scale developments, both would be devoted to large-scale components. Off-site production would

Figure 11. The fabrication process of a pavilion at the University of Stuttgart involved running a continuous spool of fiber through the pavilion, manipulated by robotic arms and a drone, controlled from a tablet device. © ICD/ITKE University of Stuttgart

> "The 'digital craftsperson' theory introduces the idea of craftspeople, with the aid of robotics, controlling the entire production process of a building, not just a part of it."

handle the bulk of high-volume pieces, while on-site production would focus on high-value items. Digital fabrication tasks, meanwhile, which work best at reduced scales, would be responsible for customized, denser proposals.

Implementation Timeframes

Given the above, and considering that the construction industry evolves at an inherently slow pace, it is unlikely that robotics will radically shift the building sector in the near future. It will be a slow, gradual process by force of circumstances. Indeed, in such a complex industry it is impossible to apply a radical change overnight, since there are countless dependencies; moreover, big construction companies work with numerous subcontractors, hampering the implementation of top-down directives. Therefore, the only possible change would be obtainable via small, orchestrated steps, entailing a cultural change. This process is more easily associated with a slow reform rather than a revolution, which requires a "digital building culture." Gramazio underlines that cultural changes usually require time and the participation of a large number of interested parties geared towards the same direction. For that matter, even the most significant innovations and milestones in the history of construction have taken a long time to be absorbed (Bock & Langenberg 2014). For this to happen, construction companies and architectural agents need to be working on it. For example, Bhooshan (2020) expresses Zaha Hadid Architects' attempt to trigger the demand of digital fabrication technologies, activating a social and cultural change by showing clients the benefits of this approach.

Besides the technical issues of the application of robotics to constructive processes, other complementary aspects and technologies need to be further developed and integrated to achieve real enhancements to the sector, leaving the way open to alternative future prospects, shifts, and many other questions for development within the current, constantly-changing environment. ■

References

Belton, P. (2018). "Why Robots will Build the Cities of the Future." Accessed 22 January 2020. https://www.bbc.com/news/business-46034469.

Bessen, J. (2016). *How Computer Automation Affects Occupations. Boston: Boston University School of Law.*

Bhooshan, S. (2020). Personal Communication [Interview] (3 April 2020).

Bock, T. & Langenberg, S. (2014). "Changing Building Site—Industrialisation and Automation of the Building Process." *Architectural Design* 84(3): 88–99. https://doi.org/10.1002/ad.1762.

Castagnino, S.; Rothballer, C.; Renz, A. & Filitz, R. (2016). "The Transformative Power of Building Information Modeling." Accessed 24 January 2020. https://www.bcg.com/publications/2016/engineered-products-infrastructure-digital-transformative-power-building-information-modeling.aspx.

Council on Tall Buildings and Urban Habitat (CTBUH). (2020). Robotics in Construction Survey. s.l.:s.n.

Davies, R., Daniel, E., Christou, L. & Lo, C. (2019). "The Future of Robotic Construction: A Solution to the Industry's Most Pressing Issues." *Design & Build Review* 53. https://designbuild.nridigital.com/design_build_review_dec19/the_future_of_robotic_construction_a_solution_to_the_industry_s_most_pressing_issues.

Gramazio, F. (2020). Personal Communication [Interview] (6 May 2020).

International Federation of Robotics (IFR). (2017). "Robot density rises globally." Accessed 15 November 2020. https://ifr.org/news/robot-density-rises-globally.

International Federation of Robotics (IFR). (2018). "Executive Summary World Robotics 2018 Industrial Robots." Accessed 26 February 2020. https://ifr.org/downloads/press2018/Executive_Summary_WR_2018_Industrial_Robots.pdf.

Matthews, K. (2019). How IIoT Will Change Robotics. Accessed January 23, 2020, from https://ubidots.com/blog/how-iiot-will-change-robotics

Sankaran, B. (2020). Personal Communication [Interview] (17 August 2020).

Søndergaard, A.; Becus, R.; Rossi, G.; Vansice, K.; Attraya, R. & Devin, A. (2020). Factory On The Fly: Exploring structural potential of cyber physical construction. In: *FABRICATE* 2020. s.l.:UCL Press, pp. 92–99.

Waters, R. (2017). Bill Gates calls for income tax on robots. Financial Times, 19 February.

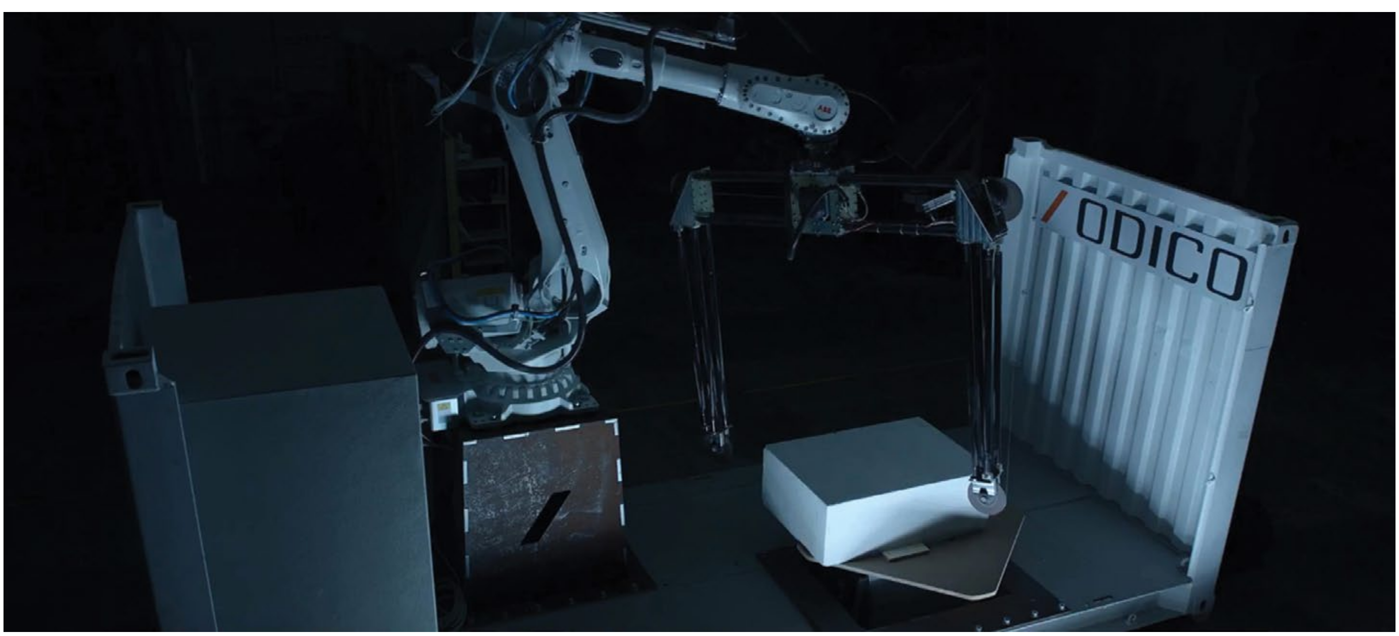


Figure 12. Odico's Factory on the Fly is an example of "near-site" construction automation, where a small, self-contained factory produces parts adjacent to the delivery site. © Odico