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Robotics in Construction: Framework and Future Directions

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Abstract

In recent years the construction sector has grown significantly in terms of investment and research on robotics and automation, yet it is still a low-tech and disjointed industry. One of the main scopes of this paper is to determine how robotic automation can provide the answers to the needs this industry has. To that end, an overall framework and development agenda of current technological innovation in the field has been outlined. Possible drawbacks and driving forces in the development of robots in the construction site have been identified. In addition, the review provides for state-of-the-art policies and regulations, as well as the short and medium-term outlook in different markets and countries. Ultimately, the forecast impact on traditional processes, construction sites, emerging technologies and related professions has been summarized in order to delineate prospective repercussions and future directions towards self-sufficiency.

Keywords: Robot; automated construction; drivers; restrains; market forecast

1. Introduction

The construction industry is one of the most ancient trades, and for many centuries its level of expertise and development has been considerably high in relation to its historical period. Despite the first moment of great development, and while some changes have been carried out, construction processes have evolved very little over the last century. The last decades' revolution can find its most glaring example in the automotive industry; the development of the assembly line introduced by Henry Ford would revolutionize the working methodology of the sequenced production of Model T piece by piece, with workers organized each one in charge of one single operation repeatedly performed. Yet, no major changes have occurred since; the obvious one is that human workers have been substituted by robotic arms in most cases, which are able to perform the operations faster, safely and with greater precision, but the general principle remains the same.

A survey conducted by García de Soto (Chen, García de Soto and Adey 2018) among sector professionals brought out three key concerns on the construction automation field. These could be summed up in the improvement of the efficiency of work processes, collaboration and capacity to increase market share, and enhancement of stakeholders' communication. Some of the mentioned factors restrain innovation in the construction market whilst some others include potential motifs to push forward the investigation.

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2. Status Report on The Adoption of Construction Robots

2.1. Restrains and Drivers

Figure 1. Operations at great heights.

The image given by the construction industry nowadays is mostly low-tech, including obsolete methods that have been maintained for centuries along with poor quality and performance. Although considered one of the largest economic markets, with about 6 percent of the global Gross Domestic Product, similar to that of the manu-facturing industry, the construction industry is currently one of the less explored fields in the application of robotic technology (Balaguer and Abderrahim, Robotics and Automation in Construction 2008). Contrary to traditional sectors, that underwent radical changes to adopt robotic systems in order to improve productivity and quality, the construction field has belatedly implemented the automation processes. Whereas in the first case robots are required to perform repetitive tasks in production lines, in stable working environments, the devices carrying out activities in construction contexts constitute a challenge for the adaptation of robotic technologies. When discussing the hassles of applying robotic concepts to the construction field, it is important to differentiate between on-site and off-site robotization. Whilst off-site automatization is already a reality, on-site operations are less likely to be changed to robotic procedures.

Some of the main factors responsible for limiting the spread of robots in construction and investment on research are the dimensions and heavy weights of the parts involved in the process (and weight limits inside buildings); scarce standardization of construction projects; heterogeneous and changing operating environment and between projects; a subsequent necessity of on-site flexibility and adaptation to use robotic resources efficiently; a need to produce a final highly defined plan and design to be able to robotize the construction work since its initiation (and robot-oriented design and methodology); high price of robotic devices and requirement of investment to alter industrial robots to fit the mentioned needs.

The uniqueness of each building project at all levels is translated to a greater difficulty to automate processes under changeful requirements. Technical and functional heterogeneity (i.e.: diverse ground conditions can be given for contiguous buildings or slight differences in usage of two adjacent homes) make a higher degree of adaptation to the environment necessary. Even in those cases where two structures are identically designed, the number of operations that can be re-iterated is lower than in automated production lines from other industries. While in production lines robots and processes are fixed on the floor and the product moves, in construction processes the final product is still and robots are required to move as the process of erection progresses in unstructured environments. Moreover, as Best and de Valence (Best and de Valence 2002) state, robots need to respond to both "decision making and situational analysis necessary for a robot to be self-directing as it goes about its assigned tasks demands very high levels of processing power contained in small, lightweight units", which traduced to construction site, means a higher level of software complexity with smaller hardware for ease of movement. Construction projects are unique and have specific requirements, assemblies are layered and a high degree of human-robot interaction is required.

A second limitation is related to the necessity to bring together robotic processes and the human workforce in a safe environment. It is important to differentiate between two types of robotic arms: caged robots and collaborative robots. The first class comprises robots that are only allowed to operate in a human-free environment, inside protective cages and sensors that stop the devices in case the cage is opened during operation. On the other hand, collaborative robots (Co-bots) are designed to work in non-exclusive environments, and if they find an obstacle, they instantaneously stop moving. This drawback is due to the lower investment in co-bots instead of existing commercial robots (useful only for a restricted target market) and requirements that need to meet in order to guarantee safety in a human-robot collaboration context. It can also be concluded that existing commercial robots are over-specified for the building industry in construction sites. Undue speed and precision are not suitable for the set conditions, and a faster investment return based on higher speed is not applicable in this case because of the limited number of processes that can be repeated identically. So much so that even the most repetitive construction task, bricklaying, cannot be compared with other industries' sequenced operations. This translates into excessive costs for an extensive application, as well as a lower return of the investment. On the basis of costs, a critical point is the lack of fluency in the communication process, from the design through completion of the work. Stakeholders involved in the process are not brought together and no standards nor automated building information protocols are set, which results in overruns on costs and reluctance to invest. For technologies and robotic systems to be efficient, and cost-effective, information sharing methods need to be improved. Additionally, researchers point out that the "lack of standardized data schema and a lack of protocol to delimitate the responsibility for information usage" is an obstacle for integrated construction processes (Chen, García de Soto and Adey 2018).

Traditionally, the quality standard and precision related to construction sites contemplate higher tolerances (range of millimeters or even centimeters) and room to maneuver, contrary to other industries where robotic systems are involved in, where the tolerance scale is of nanometers. As argued by Thomas Bock (Bock 2008), to generate products with robot-oriented methods, suppliers are required to improve off-site building products and materials in order to meet the requirements to automate operations on-site. Standardized building processes require a "flexible strategy, which includes all participating parties and allows future reusability". Both sides involved need to find a compromise; definition and control of quality conditions of materials and parts for robotics processes to be implemented to on-site applications, and adaptation to harsh and dirty working conditions of robots, originally built to work under invariable conditions and sophisticated materials and procedures. Nowadays, besides the prefabricated construction field, it is a fact that the quality of the final product delivered, as well as those from all the intervening processing steps, is low. Despite the need to work with very tight tolerances and complex processes (i.e. curtain wall joints or high-rise building structures), the reality is that building processes are still low-tech and handcrafted materials are still commonly used in on-site construction projects.

Having taken all this into consideration, one can conclude that robotic mechanisms developed for other industries are unfit to be applied to the construction field, for the excessive speed and precision of the devices, and lack of clean context repetitive action to be repeated with identical processes in homogeneous structured environments as well as the incapacity of interaction with required human workers.

In relation to the above mentioned García de Soto's research (Chen, García de Soto and Adey 2018) three crucial factors boost enhancement of efficiency of work processes in construction: safety, precision, and speed.

Safety is one of the main incentives to invest resources in the application of automation devices in construction processes. The construction industry is one of the sectors with the highest number of premature retirements and sickness related to the work environment. When activities imply an intrinsic danger for human workers, having to be performed in difficult access areas or risky environments (i.e., manipulation of poisoning or dangerous materials, heavy loads handlings, or working in locations of difficult accessibility), robots are perfect substitutes. Machines have been successfully introduced in sectors in which an improvement of labor conditions was necessary, taking over on heavy loads handling, dangerous work performance, or arduous working conditions. Robots can also deliver the small tolerance gland required to achieve the level of precision already implemented in other industries.

Safety is strongly linked to the speed factor, which makes the greatest difference in robotic implementation. Robotic arms relieve humans from tedious, repetitive and, on occasions, harsh working conditions. Having in mind the on-site application and the difference previously set, co-bots, unlike robots working on traditional assembly lines, can limit their kinetic energy and, being slower than automatic robots, are able to interact with human coworkers, not representing a potential danger to them.

The success in the application of automation devices on-site lies not in the copy of human movements and work processes, as popularly believed in regards to the collective imagery of what a robot should be up to, but to follow a robot-oriented design principle to benefit from the full potential of robots in construction. (Balaguer and Abderrahim 2008).

Apart from the aspects mentioned above, several other factors can come into play in favor of the introduction of robots in the construction field. The number of skilled construction workers is decreasing at a high pace. By the '80s, Japan was already struggling to find the qualified workforce to meet demand, in addition to facing an aging population, which propelled great investment in automatized construction systems and placed the country at the forefront of on-site robotic applications. This concern has extended to most developed countries; surveys conducted in the United States report that 70 percent of contractors found difficulties to hire skilled workers (The Associated General Contractors of America 2019) and workers' average age is 43, an increase of almost 10 years in the last decade (Belton 2018). Furthermore, urban areas contain an always increasing number of inhabitants and cities grow at a faster pace, which affects the need for infrastructure, public transportation and affordable housing. This, together with the increasing lack of skilled workers and resources, reflected in the steadily increasing cost of building, as well as the constant need for reconstruction and infrastructure repairs, requires to introduce high speed and low-budget processes, possible only with the development of robotic systems.

Construction fields include a great number of processes that do not require complex robotic systems to alleviate human workers from hazardous activities that must be considered. It is doubtless that the ultimate goal would be to incorporate on-site highly versatile devices capable of substituting human workers in every construction task and without restraints. When there is no workforce accessible or with the required expertise, there is room to develop a robot to make up for the gap and perform the needed activity.

2.2. Policies, Market Forecast and Regulation

Despite the current hindrances, the necessities to integrate robots in the construction sector, and in other fields as well, have boosted both public and private initiatives all over the world, in terms of policies and economic investments; indeed, these aspects need to be coordinated to be effective, since an increased matching of interests among the different stakeholders is required to promote the implementation of robots (Chen, García de Soto and Adey 2018).

Furthermore, different public-private organizations have been founded since the application of robotics is considered crucial and it is expected to have a massive impact on the economy; for example, SPARC, which was established in 2014 between the European Commission and around 180 private companies and research institutions, is the main initiative in Europe that aims to improve the robotic strategy by linking the scientific knowledge to the marketplace. Among other investments and within the seven-year framework program "Horizon 2020", a funding of 2.8 billion euros, of which one third coming from the European Commission, has been allocated by this association

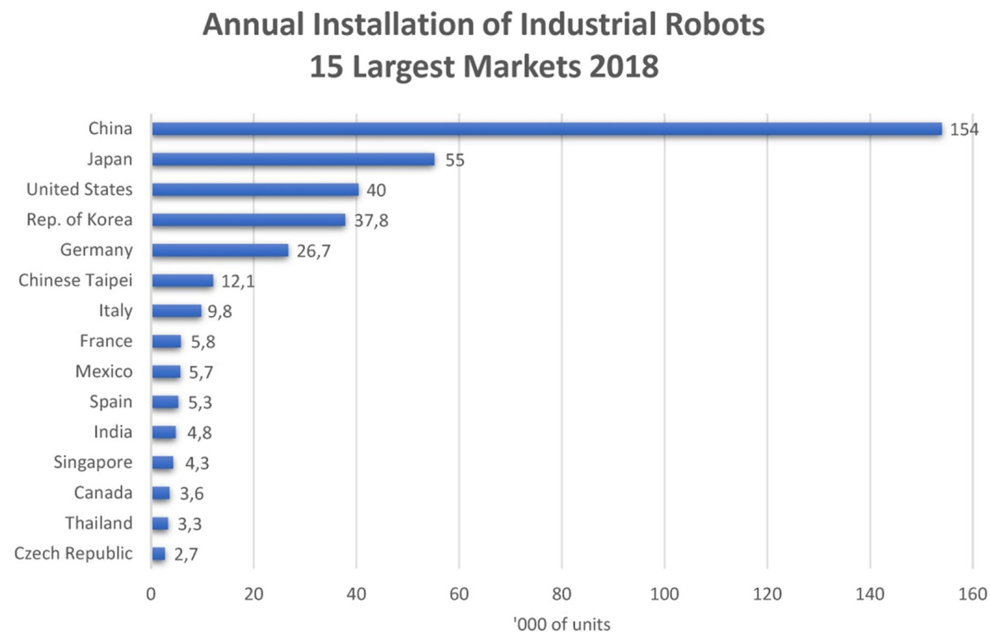

Table 1. Annual Installation of Industrial Robots - 15 Largest Markets 2018

(European Commission 2014).

In 2014, the Japanese government set the purpose to start off a "new industrial revolution driven by robots" within the "Japan Revitalization Strategy". At the same time, the "Intelligent Robot Development and Promotion Act" was enabled in South Korea (Sang-mo 2018). The following year the "New Robot Strategy. Japan's Robot Strategy - Vision, Strategy, Action Plan" was published, not only to develop robotics in competition with other countries but also because of the necessity of dealing with the internal problem of the aging population (METI 2015).

On the other hand, a national strategy for robotics development has not been promulgated yet in the United States, as evidenced in the recommendations outlined by the American Society of Mechanical Engineers (ASME 2019); in addition, there is a not so favorable tax treatment of capital expenditures in this country, as is also the case with the UK, and consequently manufacturers are less inclined to invest (Atkinson 2019) (Dellot and Wallace-Stephens 2017). Anyways, the American is one of the five major robot markets and it grew for the eighth consecutive year in 2018 accounting, in the same period, for the 74% of global sales volume together with the other four nations (China, Japan, Republic of Korea and Germany) (IFR 2019).

Furthermore, besides the governance policies, some of the most advanced nations in this sector can rely not only on solid public initiatives to support manufacturers but also on tax policies that encourage the adoption of sophisticated technology, such as robots (Ezell 2011).

China, which has the biggest robot market in the world since 2013 (IFR 2014), issued as well several national development plans for its industry sectors, such as the "13th Five-Year Plan (2016-2020)" and the "Made in China 2025", which identify the enhancement of robots as a key point for their actuation. Hence China, which has specific plans of maintaining its world-leading position in this field and further increasing the gap with the other nations by enhancing the quality of its products, allocates huge amounts of funding, more than any other country. For example, the Guangdong provincial government intends to supply 943 billion yuan (approximately $135 billion) to encourage the "machine substitution" of the companies established in its territory. As well, Anhui province declared to spend 600 billion yuan (approximately $86 billion) to achieve an industrial enhancement through ro−botics (Atkinson 2019) (Dellot and Wallace-Stephens 2017).

The above-mentioned policies and data also involve robotics related to the building sector; construction robots' market, that includes the whole range of advanced devices, is currently growing and is expected to continue to do so in the next years, but the estimates differ depending on the research institute that conducted the market investigation. Specifically, MarketsandMarkets forecasts that the market in question should reach $166 Million by 2023, at a CAGR (Compound Annual Growth Rate) of 16.8% between 2018 and 2023 (MarketsandMarkets 2018); Research and Markets states instead it is expected to amount to $126.4 Million by 2025 (Research and Markets 2019), while Tractica predicts an increase in market revenue from $22.7 million (2018) to $226.0 million by 2025. Furthermore, the same company estimates that more than 7,000 construction and demolition robots will be deployed in that period (Tractica 2019). Differently, BBC News reported an analysis of QY Research that foresee the global market to more than double in size by 2025, reaching $420M

(Belton 2018). Similarly, Transparency Market Research indicates a value of $470.61M presumed by 2026, expanding at a CAGR of 10.4% (Transparency Market Research 2019). A different datum is provided by IDC, which reports that the worldwide spending on robotics systems and drones will reach $210.3 Billion by 2022, with a CAGR of 20% (IDC 2018).

Another important issue linked to the diffusion and application of robots consists of the completion of the related standards. The regulations regarding robots, which are under constant updates, are currently drawn up by ISO Technical Committee 299 with the title "Robotics" covering different matters, such as performance criteria, modularity, and vocabulary (ISO 8373 2012). Furthermore, standards about industrial and service robots are especially focused on safety (ISO 10218-1, ISO 10218-2, ISO/TS 15066) (ISO n.d.).

3. Future Perspectives & Research Needs

3.1. Implications and Consequences

Opinions diverge on the future of robotics and impact on jobs and construction ways of doing. IFR (IFR 2018) 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, not without the fear of workers being replaced and certain professions' extinction. These occupations have undergone different transformations; several have indeed disappeared, but some have been transformed and others have been created to operate with new automated mechanisms, generating great demand (i.e., competences of secretaries have transformed from managing tasks to managing computing systems).

IFR (IFR 2017) sets a series of possible future impacts on employments related to a widespread of robots within the working environment. The organization submits that automation is responsible for generating new business models as well as making nations and companies to be competitive (IFR 2018), but others point out that they are also responsible for extinguishing traditional crafts. In this regard, James Bessen (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 demand of employment, which would imply job losses. Yet, most agree on the fact that automation leads to an increase in the number of business opportunities. And not only, but also productivity rises can prompt greater demand for workers in the sector (Bessen 2016). This enables the apparition of new business models linked to both provide new goods and services, and help existing companies to absorb the required changes to be able to compete in the construction market, improving in terms of efficiency and flexibility. Economists do also agree in large part that this increase of productivity on account of process automatizing is crucial to the improvement of the GDP of developed countries.

Experts concur too that the implementation of automation procedures will lead to the emergence of new professional figures. Many different projections and prognosis have been conducted during the last years in this regard, to which it is interesting to elaborate a distinction; jobs are not the same as activities. IFR (IFR 2017) 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. Various researchers acknowledge that by 2057 almost half of the current construction jobs could be substituted by robots (Belton 2018). On the other hand, supporters of the incorporation of robots pinpoint that only a few medium and low-skilled jobs would be replaced, whilst the spectrum of high-skilled workers will expand to meet the need of robot operators. Many experts concur that medium-skilled workers would require training to gain further knowledge and competences to guarantee the preservation of jobs in a new highly technicalized work environment, going from performing repetitive tasks to monitoring robots which perform them (IFR 2017). With this in mind, the question is if a relocation or upskilling is a real possibility. One must consider that not all people have the aspiration or are capable of performing highly-qualified jobs or become an IT expert, and these will be unemployed if robots occupy their jobs. And it is important to note that, in last instance, humans need to work and an occupation is required to live, because work dignifies humanity. In this regard much has been discussed, as some politicians and tech industry leaders, such as Microsoft co-founder Bill Gates, have proposed the incorporation of this tax dedicated to subsidizing people whose job has been substituted by

Figure 2. Bolting Operation on the Empire State Building, 1930.

robots and to promote a gradual and smooth transition to automation (Waters 2017). On the contrary, IFR (IFR 2017) believes the introduction of a robot tax is no guarantee a social welfare state but a deter on robotic investment. In any case, most agree on the fact that governments need to work on coverage of social payments out of revenues generation.

Robots are intended to be a part of the construction site, as said, both substituting human workers and working collaboratively with them. Ideally, co-bots would complement human workers and relieve them from performing dull activities and those that require a higher effort; machines could work in parallel and replacing workers during lunch breaks or at night, including gestures and natural speech translation to facilitate message transmittal. Still, it is important to bear in mind that existing fabrication and building processes are thought to be developed by human workers, and not machines. In this regard, Hwang asserts that "the construction industry needs to think 'out of the box' and seek alternatives" to these traditional manual operations, and instead perform from the perspective of robotic operating modes (Hwang, Lee and Kwon 2005).

3.2. Technologies to be Integrated

As previously mentioned, the communication fragmentation between the design and construction phases is today a drawback. Researchers believe that the potential for innovation and productivity will depend on the conjunction of information from these two stages through the implementation of a continuing process. A study by Boston Consulting Group (BCG) reflects that by 2026 the digitalization of non-residential construction is expected to result in worldwide annual cost savings of 10 to 21 percent on diverse stages of a project (Gerbert, et al. 2016). As set by BCG (Gerbert, et al. 2016), efficient information exchange will enhance accuracy and real-time decision making, along with reductions on delivery times, besides assisting in a significant reduction of material as a result of the decrease of inconsistencies in the final stages of the construction process.

Considering the above, robots will substantially transform the approach to the design of construction projects. The implementation of Building Information Modelling methodologies (BIM) and new software applications, such as virtual reality, augmented reality or holograms, call for the integration of robotic systems and design software on a central platform, with access to a large database containing construction knowledge. 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.

At the moment, extended networks and signal repeaters are required in construction works more than 200 meters in height. 5G technologies, together with Industrial Internet of Things (IIoT) solutions, enable robot control on high-rise buildings and enhance their autonomy and response speed. The implementation of this technology will open 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). This results in the possibility for robots to delegate processing activities to remote servers in order to take advantage of their computational power, without the need of installing expensive robot hardware and software, a field known as Cloud Robotics. Furthermore, managers will be able to monitor and synchronize the activities of numerous IIoT robots and across different locations, and devices will issue own performance statistics and predictive maintenance (Matthews 2019). All these technologies are seen as the prelude to Artificial Intelligence (AI).

4. Conclusions

The purpose of this paper was to frame and assess the context within which robotic applications in the on-site construction industry are being developed. This has led to conclude that whilst there has been some progress on the development of technologies in regards to the construction industry, it does not bear comparison with other industries such as the automobile or manufacturing even though it is one of the leading economic markets.

Challenges and drivers in the implementation of robotic procedures in the field of construction have been delineated. The unstructured nature of building sites and complexity of required tasks, the high degree of human-robot interaction required, the high price of robotic devices, the necessity of relevant investment in robotic technology applications, together with obsolete methods, poor quality and perfor-mance and miscommunication hassles between the diverse agents have been identified as the main difficulties. While fully automated processes are still far from a date and further developments in robotic technologies must be implemented, researchers reflect that the three main drivers pushing forward research in the field are safety, speed and precision. In this regard, the introduction of innovative technologies, BIM methodologies, 5G, IIoT and Cloud Robotics, among others, should lead to a widespread of robotics in the construction environment by reducing the cost of robots, improving the communication between different stakeholders, and enhancing process control. Ultimately, Artificial Intelligence can be the final step to the successful incorporation of robotic devices into the construction work field. conversely, the findings indicate that major motivations reside in the search for an increase in safety, speed and precision, but also in a growing lack of skilled workers, aging population and the need to save resources.

In this context, it has been found that different organizations, entities and researchers have tried to forecast possible future impacts to robotic applications to the construction industry in regards of employment, business models, working environment, and human worker-robot collaboration. One of the most supported hypotheses is that medium-skilled workers will be largely substituted by robots, in other cases complemented by collaborative robots in the development of certain strenuous, repetitive tasks, and new professional figures will arise.

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