Robotics in the construction industry: state of the art and future opportunities

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Abstract -

This paper discusses the results of a survey regarding state of the art and possible future opportunities for the application of robotic technologies in the construction industry. The survey was conducted by submitting two distinct questionnaires to Arup's[1] most experienced technical and business leaders. The first questionnaire was designed in order to understand the state of the art of robotic technologies in the construction industry, while the second one aimed at identifying promising application scenarios from both the industry and the research point of view. The paper discusses how the questionnaires have been designed and presents the corresponding results.

Keywords -

Robotics; Construction industry; Construction Robots;

1 Introduction

The first applications of robotic technologies to the construction industry were designed in Japan during the 70's, in order to improve the quality of prefabricated elements for modular residential buildings. Since then, robots started spreading in the construction industry, slowly moving from factories to actual construction sites [1, 2, 3]. Differently from other industry fields, where the introduction of robotics technologies radically changed the way human workers operate, the construction industry has not fully experienced its "robotic revolution" yet. As a result, various operations that require high power and/or high accuracy (such as panel positioning, plumbing, material handling) are still manually performed by human workers in very inefficient and dangerous ways. Not by chance, some studies strongly suggest that productivity in the construction industry has been declining over the last decades [4] and that the conventional construction paradigm has reached its technological performance limit [5]. Even though the barriers that are preventing robots to spread within the construction industry are well known, some recently emerged trends started fostering the adoption of novel technologies.

As far as scientific research is concerned, there is no doubt that also the robotics community has demonstrated a growing interest towards applications in the construction industry in the last 15-20 years. Not by chance, the number of scientific publications targeting construction scenarios has experienced a significant growth over the last two decades, as it is demonstrated by Figure 1. From the application point of view, these scientific publications have confronted almost every construction-related application context. Naturally, heavy-duty operations have been tackled, like for instance façade installation [6, 7, 8], forestry [9], mining [10] and generic earthworks [11, 12]. Several solutions have also been developed in order to facilitate inspection of buildings and infrastructures [13, 14, 15]. Finally, in accordance with the trends that will be introduced in the following sections, more recent contributions tackled novel application contexts like for instance realization of wooden buildings [16], interior and exterior renovation [17, 18, 19, 20], additive manufacturing [21, 22] and also decommissioning of nuclear power plants [23, 24].

On the other hand, as far as research topics are concerned, construction-related contributions have explored both consolidated and recent topics in the robotics field: inverse kinematics calculations [25, 26], control architectures [27, 28, 29], trajectory planning algorithms [30], teleoperation strategies [31, 32], Human-Machine Interfaces (HMIs) [33, 34], autonomous vision [35, 36], [37], usage of Unmanned Aerial Vehicles (UAVs) [38]. Another topic that is worth mentioning is represented by the integration with Building Information Modelling (BIM) [39, 40, 41].

Given this scenario, it is clear that both a thorough review of the state of the art of robotic technologies in the construction industry and a detailed assessment of their implementation at different stages of the construction process could be beneficial to identify future research directions and to steer future development activities. With this in mind, the authors realized a survey in order to (i) draft a detailed picture of the state of the art, (ii) identify promising application contexts from both the industry and the research point of view and (iii) underline what skilled professionals expect from robotic technology in the con-

[1]Arup's website: `https://www.arup.com/`

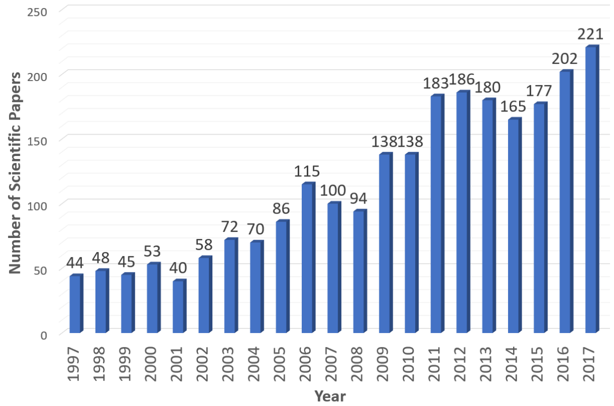

Figure 1. Number of publications labelled with the keywords "construction robotics" and/or "construction robot" over the last two decades. Data extracted from Google Scholar.

struction industry. In detail, the survey has been realised by submitting two distinct questionnaires to Arup's most experienced technical and business leaders. The first questionnaire aimed at defining the current scenario, while the second one aimed at identifying possible future opportunities. This paper discusses how the questionnaires have been designed and presents the corresponding results. Section 2 deeply discusses barriers, drivers and trends that are influencing the adoption of robotic technologies in the construction industry. Then, Section 3 introduces the first survey and presents the corresponding results, while Section 4 describes the methodology and the results of the second survey. Finally, Section 5 reports some hypothesis regarding future opportunities.

2 Robotics in the Construction Industry

As mentioned before, the spreading of robotic technologies within the construction industry has historically encountered strong resistance, due to several well known barriers. Nowadays the situation is rapidly changing thanks to some recently emerged drivers that are accelerating innovation processes within the construction industry. Moreover, these drivers originated some clearly recognizable trends that are changing the way buildings are planned, built and maintained. In the remainder of this Section these barriers, drivers and trends are explained in detailed.

2.1 Barriers

The main factors that have prevented the spreading of robotic technologies in the construction industry can be listed as follows:

- **Site-related Challenges**: the inherently unstructured nature of construction sites prevents straightforward integration of robotic technologies already used in factories;

- **Sceptical Attitude**: the main stakeholders involved in the process (construction companies, clients and regulatory bodies) are characterized by a strong tendency to stick to well consolidated practices rather than to innovate and adopt novel technologies;

- **Complexity of the Supply Chain**: the number of different stakeholders and the fragmentation of the supply chain entails a strong inertia towards innovation due to extremely varying interests and needs;

- **Variety of the Markets**: regional markets have intrinsic differences (regulations, cost of materials, cost of workforce, quality requirements for products, etc.) that imply different requirements;

- **Variability of Buildings Typologies**: every building can be considered as unique due to the many differences that apply to its shape, materials, components used and locations. Consequently, flexible and easy to adapt technologies are required.

2.2 Drivers

Moving to the drivers that are fostering innovation processes within the construction, the following ones were identified:

- **Scarcity of Resources**: cost of materials traditionally used for construction purposes is increasing, while availability is decreasing;

- **Urbanization**: in order to build within densely populated urban areas it is necessary to rationalize the way buildings are designed and to employ compact and flexible machines in the construction process;

- **Ageing Workforce**: construction workers are rapidly ageing and technologies that can reduce physical effort and fatigue will be increasingly needed;

- **Connectivity and Convergence**: construction workers are becoming more and more used to new technologies, thus making it easier for them to adapt to the introduction of robots in their workplace;

- **Environmental Friendliness**: construction sites will need to progressively reduce polluting emissions, thus fostering the diffusion of electric powertrain systems;

- **Safety**: safety-oriented technologies will play a crucial role in reducing the number of accidents and injuries, in line with latest safety regulations.

2.3 Current Trends

Finally, robotics-related trends that are currently gaining momentum in the construction industry include:

- **Additive Manufacturing**: 3D printing simultaneously allows to rationalize the consumption of resources and to customize products to specific needs;
- **Internet of things**: the possibility to continuously acquire and share data is enabling novel paradigms, like for instance remote control of machines and predictive maintenance;
- **Integration with BIM**: the availability of 3D and 4D (time) information models will foster robotization of construction sites by making all the design information and the data collected on-site available in real-time to construction robots. As a result, quality of planning, construction and maintenance processes will increase, while execution time will decrease;
- **Augmented an Virtual Reality**: integration of AR an VR will improve training strategies and allow effective remote operations of robots [42, 43, 44];
- **Circular Economy**: construction industry is moving from a linear consumption model (use-consume-dispose) towards a circular one (use-recover-recycle). In this context automation and digitalization will act as key enablers.

3 First Survey: State of the Art for Robots in Construction

The first survey aimed at understanding the current occurrence of advanced construction machines and robots in key construction sectors, through the life-cycle of a project. To do so, a decomposition of the construction process life-cycle has been proposed, as well as six different application sectors have been prioritized for the investigation.

3.1 Construction Process Life-cycle

The default life-cycle of a construction project can be decomposed into the following main phases (see also Figure 2):

- **Site investigation**: this phase includes any action to assess the status of a construction site both for existing buildings/infrastructures and new built. It could include scanning of a building interior, inspection of basements as well as geotechnical survey;
- **Demolition**: this phase includes the set of actions needed to demolish a portion or a whole of a building/infrastructure. Might also include disassembly when possible and requested by the project;

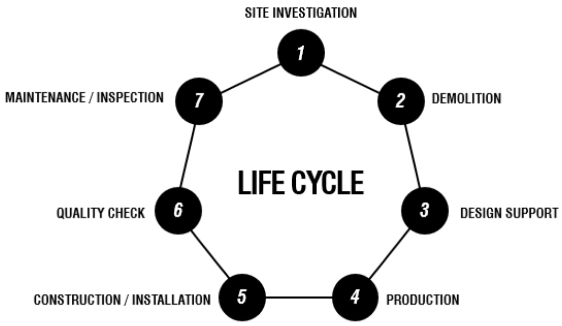

Figure 2. Construction Process Life-Cycle.

- **Design Support**: this phase includes actions to allow a more precise and actual design process, allowing the designer to know more details about any pre-existence at building/infrastructure or site level;
- **Production**: this phase includes the set of actions performed in the making at either the component or at the system level. For the purpose of this paper, we refer to production specifically for in-factory processes;
- **Construction / Installation**: this phase includes the set of actions performed during either the construction or the installation of a building/infrastructure portion or its whole. For the purpose of this paper, we refer to construction and installation referring to on-site processes;
- **Quality Check**: this phase refers to the actions performed at completion of the construction and installation process to assess the quality and the right execution of the process;
- **Maintenance / Inspection**: this phase includes the set of actions to assess the status of a building/infrastructure until its end of life.

These phases are seen as the most meaningful, and those ones where a construction robot could have a significant impact.

3.2 Priority Sectors for Application

On the basis of their experience and market knowledge, Arup's experts identified a set of high priority sectors for application in construction to be investigated within the survey. As shown in Figure 3, these sectors are:

- **Building Cladding**: this sector includes all the parts (components and systems) used at the level of the building envelope being this of any size, form and complexity, from small rain-screen panels to large unitized façade panels;

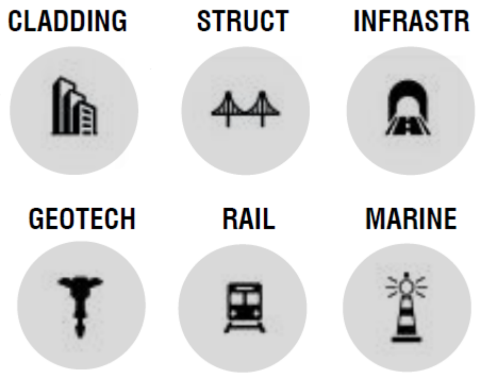

Figure 3. Priority Sectors for Application.

- **Building Structures**: this sector comprises all the parts (components and systems) used to provide adequate structural performance to a building;
- **Infrastructures**: for the purpose of present research, we considered this as the sum of the parts (components and systems) used to make a tunneling project;
- **Geotechnical Engineering**: for the purpose of present research, we considered this as the sum of the processes necessary to perform surveying and construction of underground areas or parts of a building/infrastructure;
- **Railway**: for the purpose of present research, we considered this as the sum of the parts (components and systems) used to make a railway project;
- **Marine Engineering**: for the purpose of present research, we considered this as the sum of the processes necessary to perform surveying and construction of marine and cost areas or parts of a submerged building/infrastructure.

3.3 Examples of Case Studies

In order to clarify the methodology used to conduct the survey, two distinct case studies have been reported here. The first example refers to the line of remotely operated demolition machines realized by Brokk[2]. Figure 4, shows some data regarding weight ($500 - 1300\ kg$), maximum payload ($80 - 1200\ kg$), maximum reach ($2.00 - 9.50\ m$) and travelling speed ($0.60 - 0.70\ m/s$) of the different machines. More interestingly, the diagram also reports the result of the survey in terms of mapping between the specific case study and life-cycle phases (in this case only demolition), and between the machine and the corresponding sector (cladding, structural and infrastructural engineering).

[2]Brokk's website: `http://www.brokk.com/`

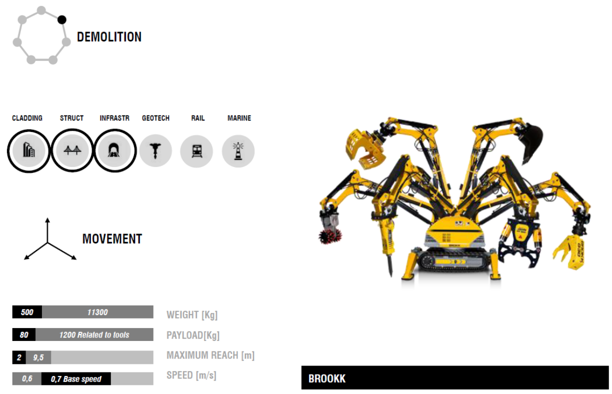

Figure 4. First Survey: remotely operated demolition machines produced by Brokk.

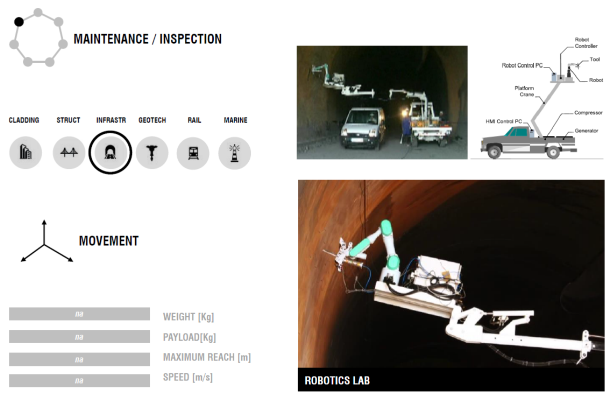

Figure 5. First Survey: Tunnel inspection robot developed by Universidad Carlos III de Madrid.

A different case study is described by Figure 5, where an example of tunnel inspection robot is considered. Clearly, this case study robot has been matched with the maintenance/inspection phase and with the infrastructural engineering sector.

3.4 Survey Results

During the survey a total of 52 construction robots have been identified and categorized by Arup's consultants. Figure 6 shows the final results of the investigation from a tow-fold perspective. In the heptagon on the left, case studies were mapped to the different phases of the construction life-cycle. Data show that the vast majority of currently available construction robots are strongly focused on maintenance and installation tasks. As far as inspection tasks are concerned, the spreading of robots is almost surely due to the possibility to take advantage of high position accuracy in order to automate repetitive and specific tasks. Moving to installation tasks, the possibility

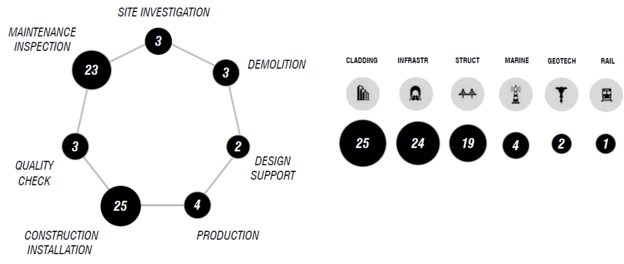

Figure 6. First Survey: overall results.

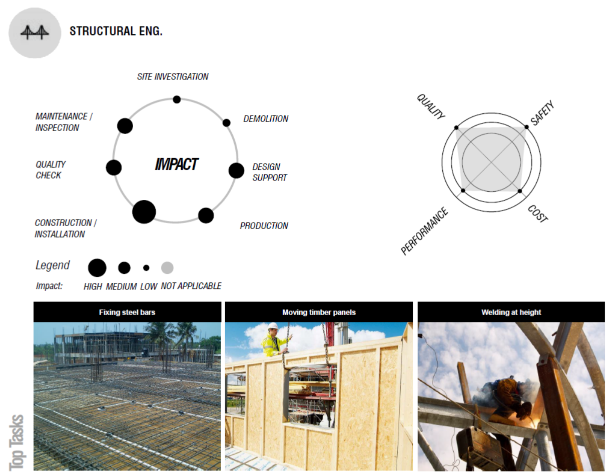

Figure 7. Second Survey: Structural Engineering sector.

to move relatively low (high) payloads with high (limited) accuracy is particularly appealing. Notably, the survey identified a low number of robotic applications in the design support, production and in the quality check phases. This is possibly due to some of the aforementioned barriers: sceptical attitude towards new technologies, complexity of the supply chain and heavily unstructured nature of on-site operations.

Moving to the diagram on the right, where the identified case studies were mapped to the considered application sectors, it can be seen that several robots were found in the cladding, infrastructural, and structural sectors, while very few examples exist in geotechnical, railways, and marine engineering. A possible interpretation of these data consists in relating the number of technologies with the features of the corresponding working environment. In other words, the more the environment is unstructured and exposed to dust and weather conditions, the more difficult it is to realize robust and effective robots. It is worthwhile to mention that, as shown in Figure 4, a single robot can be mapped to one life-cycle phase (application sector) or more.

4 Second Survey: New opportunities in the construction industry

The second survey had a different ambition, namely to identify where the highest potential is currently seen within the building life-cycle and according to the six priority sectors identified before. To reach this goal, Arup's experts have been asked to assign a score to the relevance of robotic technologies, in the specific sector, at a specific life-cycle stage. Possible scores were:

- **High**: 3 points;
- **Medium**: 2 points;
- **Low**: 1 points;
- **Not Applicable**: 0 points.

Then, they were requested to evaluate, in each sector and using the same scale, the impact of robotic technologies on the following key indicators:

- **Quality** of the construction;
- **Safety** within the construction site;
- **Cost** for the operations;
- **Performance** of the construction.

4.1 Examples of Application Sectors

In order to demonstrate how the authors conducted the second survey, data regarding two different application sectors are detailed in the following. The first one pertains the structural engineering sector. As it can be seen in Figure 7, the impact of novel robotic technologies in this sector is considered as "high" in the construction / installation phase, "medium" in design support, production, quality check and maintenance phases, and "low" for all the other phases. Arup's experts also evaluated a high impact in terms of safety and quality metrics, and a medium impact on cost and performance. As far as types of operations are concerned, some promising tasks identified in this sector are fixing of steel bars, placing of wooden elements and welding at height.

A different example is displayed in Figure 8, where the infrastructure sector is analysed. The impact of innovative technologies has been considered as "high" in almost all the phases, except production ("medium") and site investigation ("not applicable"). As far as key indicators are concerned, the result is the same with respect to the previous example. Finally, the most interesting tasks to automate are concrete spraying, tunnel inspection and tunnel boring.

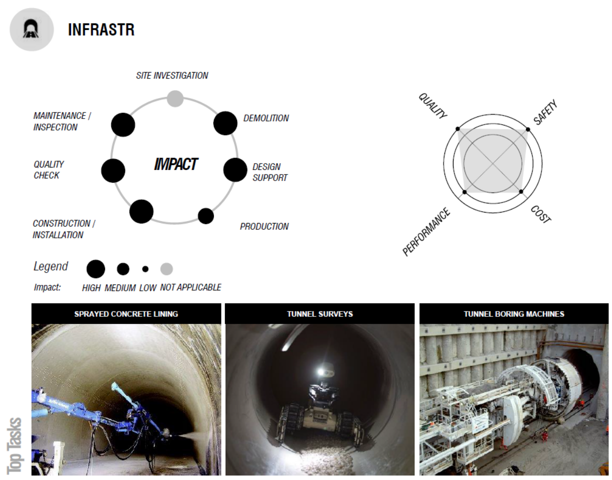

Figure 8. Second Survey: Infrastructure sector.

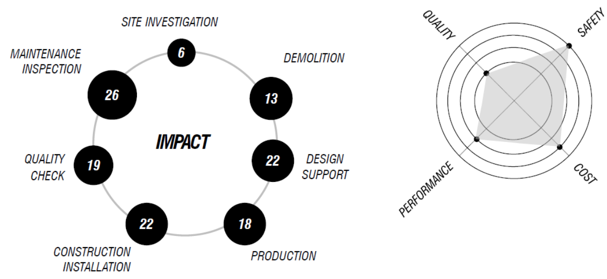

Figure 9. Second Survey: overall results.

4.2 Survey Results

In order to sum up the results of the second investigation, the two diagrams contained in Figure 9 have been realized. The one on the left shows the overall relevance of hypothetical new robotic applications to be implemented at the different stages of the construction life-cycle. Global scores have been computed by averaging the total scores assigned to each life-cycle stage over the different application sectors. Having in mind the results of the first survey (see Figure 6), the fact that maintenance and installation are confirmed to be the top-two phases comes at no surprise. Furthermore, the fact that a significant potential has been identified in the design support, production and quality check phases is in line with the conclusions of the first investigation. Finally, also demolition has been judged as an appealing stage since, in the context of a circular economy, the idea itself of demolition changes from destruction to de-construction, thus making position accuracy a valuable advantage.

On the other hand, the diagram on the right shows the average score assigned to each key indicator. According to Arup's experts, novel robotic technologies will have a substantial impact on safety and cost (which is quite straightforward). On the other hand, a lower impact is foreseen in terms of quality and performance, mainly because the capability to deal with heavily unstructured environments is still an open issue from both the research and the industry point of view.

5 Conclusions

This paper presents a survey activity aimed at defining a clearer picture of the current scenario of robotic in the construction industry. The investigation also intended to identify future opportunities for research and development activities. The survey involved Arup's most experienced technical and business leaders and was performed by means of two distinct questionnaires. The paper motivates the design of these questionnaires, presents some example of detailed analysis and discusses the overall results. In the end, Arup's experts identified demolition, design support, production and quality check as the construction phases where new robotic technologies could have larger impact in the next few years, in terms of improved safety and reduced costs and across several application sectors. Clearly, in order to develop such machines, the capability to robustly perform complex tasks inside heavily unstructured environments remains the most demanding challenge to tackle from the research point of view.

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