

CHAPTER (X)

SAFETY RISK FACTORS IN THE USE OF CONSTRUCTION ROBOTS

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ABSTRACT

Technological advancement has led to the increased reliance on machines in place of human construction workers. Advanced robotics and automation systems are therefore becoming commonplace on construction sites albeit used mostly alongside construction workers since many trades still require human skills. As a result of these hybrid robot-human industrial scenarios, the EU commission of Safety and Health has forecast that the greatest occupational safety risks over the coming years will emanate from the interactions between humans and machines in most industrial sectors. Despite the potential efficiency gains from the use of robots or robotic devices in construction, the emergent risks need to be identified, understood, and mitigated through various interventions including risk assessment and worker training. The main aim of this chapter is therefore to identify and list the health and safety risks associated with construction robot use. The study adopts an expert desk research and workshops following focus group methodological approach. Based on the systematic analysis of data and expert opinion, 59 risk factors were identified together with the potential sources of each risk. The most prevalent risks source was identified as the work environment (work design failure and procedural failures). The study further highlights the dominance of physical risks albeit highlights the emergence of psychosocial risks associated with the use of all types of construction robots. The findings focus primarily on the prevalence or likely existence of the risks factors thus further studies need to be conducted to establish their impact or importance in practice. The list of risk factors provides comprehensive guidance for the development of safety training and guidance material for risk assessment in this emergent risk area.

Number of Figures: [1]

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Introduction

Studies carried out recently have revealed lower levels of productivity in the construction industry when compared to other industries where automation is more commonplace (McKinsey and Company, 2017). According to Bock (2007), traditional construction methods have reached their limits and the next level is for construction to adopt more automation and robotics technologies to help modernise as well as improve productivity, efficiency, and performance. The adoption of robotics and smart automation has the potential to address the numerous challenges facing the construction industry (Delgado *et al.*, 2019; Trujillo, 2020). Despite the promise of improved performance, this shift towards robotics represents a significant change in paradigm in ways of working thus introducing new risks. Initially, it is envisioned that robots will be introduced in a hybrid construction environment where human workers collaborate or work alongside these machines (Bock *et al.*, 2012). Despite the various safety developments in robotics, there remains some risk associated with these hybrid industrial environments (Martinetti *et al.*, 2021). This chapter therefore aims to identify and review the health and safety risks associated with the use of construction robotics. The chapter commences with background literature about construction robotics, which covers the type of robots and autonomous equipment /devices as well as associated safety risks. This is followed by the research methods section. Subsequently, the results and their discussion are outlined, which lead to the concluding remarks.

Construction Robots

The definition of a construction robot is known to cover a wide spectrum of autonomous and teleoperated systems (Bock, 2007; Bogue, 2018). A very simple definition of a robot is a mechanical or virtual intelligent agent that can perform tasks automatically or by remote control (Cobb, 1998; ISO 10218; Zhang, 2018). The term robot and robotic devices is synonymous with almost every machine that incorporates an automated component (Cobb, 1998). There is a myriad of definitions for construction robots with the following commonly associated features, autonomy, semi-autonomy, teleoperation, and pre-programmed control systems among others (Delgado *et al.*, 2019).

The construction industry, however, continues to be plagued by several challenges including a shortage of labour due to an ageing workforce (Torku *et al.*, 2021). In addition, there are serious performance issues relating to the quality, schedule, safety, and complex environments that could be improved through the adoption of automation and robotics (Bock *et al.*, 2012; Bogue, 2018). However, moving the industry to the era of automation and robotics has been challenging due to a myriad of implementation challenges including resistance to change, economic and technical factors (Delgado *et al.*, 2019; Trujillo, 2020). The technical challenges include safety issues associated with the design of robots as well as design of the robotic work environment (Vasic and Billard, 2013). Furthermore, there remains a general lack of understanding of emergent safety risks especially in hybrid site scenarios envisaged (Vasic and Billard, 2013; ISO 10218).

Types of Construction Robots

Robots are generally categorised based on several factors. There are categorisations that are based on the environment in which the robots operate, what they are used for and their design features. Another common distinction is based on mobility characteristics i.e., fixed and mobile robots (Rubio *et al.*, 2019). These two types of robots have very different working environments and therefore require very different capabilities (Ben-Ari and Mondada, 2018). Construction robots broadly fall within a category referred to as industrial robotics (Bock, 2007). Delgado *et al.* (2019), categorised construction robots based on their function and area of deployment: Off-site automated

prefabrication systems; On-site automated robotic systems and; Drones and autonomous vehicles; and Exoskeletons (Bock 2007; Bock et al., 2012). Thus, a main factor in categorising construction robots is environment in which they operate (i.e. offsite such as in prefabrication factories or onsite) (Gharbia *et al.*, 2020). They may also be categorized based on the tasks they perform such as demolition, 3D printing, cutting, bricklaying, welding, and transport (Taylor et al., 2003; Delgado *et al.*, 2019). In other industrial settings they are often classified based on mobility characteristics (i.e., fixed or mobile robots). Mobile robots may be further classified as wheeled, legged, swimming, flying (aerial) (Rubio et al., 2019). Another categorisation used in robotics is the level of collaboration with humans which may include collaborative robots, exoskeletons, and wearable robots (Zhang *et al.*, 2018). One robot may share several of the above characteristics or fall within several categories. Another suggested categorisation proposed by Soffar, (2019) is mainly based on design and mechanical features as outlined: Linear robots (including cartesian and gantry robots), which are characterised by two or three principal axes that move in a straight line; Articulated robots which refer to robots with rotary joints for example SCARA robots (Selective Compliance Articulated Robot Arm); Parallel robots (delta) which are composed of a mobile platform connected to the base by a set of identical parallel kinematic chains; and Cylindrical robots which have rotary joint at the base and a prismatic joint to connect the links (Soffar, 2019).

Known construction robots include demolition robots, welding robots, autonomous or teleoperated construction plant and equipment, Unmanned Aerial Vehicles (UAVs) and exoskeletons (Taylor et al., 2003; Delgado et al 2019; Gharbia *et al.*, 2020). Also, there are robots for cutting operations, bricklaying and 3D printing and contour crafting (Taylor et al., 2003; Delgado et al 2019; Gharbia *et al.*, 2020). In particular, exoskeletons are being proposed as a viable solution to the labour intense hybrid site environment (Bock et al., 2012). Exoskeletons are mechanical suits that help to increase the strength, speed, and agility of an average worker in carrying out activities on site. Exoskeletons can be classified as wearable robots, and when used can improve productivity by allowing workers to lift heavier loads (Bock et al., 2012). Another popular and emerging robotic device is the UAV which are used for a variety of tasks including transport, surveying and monitoring (Kaamin et al., 2017; Delgado *et al.*, 2019). Three-dimensional (3D) printing and contour crafting is also becoming commonplace because of advances in digital modelling, design and fabrication. The machines for 3D printing and contour crafting work by extruding or moulding different kinds of material such as molten plastic, concrete, other composites, and metal through nozzles under the guidance of computer programs and digital models (Zhang et al, 2018).

Safety Risk Factors in Construction Robot Use

Despite the benefits of using robots, they may also introduce other risks to industrial environments. Asimov's three laws, which are based on functional morality assumes that robots have sufficient agency and cognition to make moral decisions (Asimov, 1984). To date, however, many industrial robots are not intelligent enough to make holistic decisions regarding safety hence eliminate risk to humans. Safety risks, thus remains one of the primary concerns in robot use especially risks emanating from human and robot interaction (Vasic and Billard, 2013; Jansen et al., 2018). There is a growing number of standards that attempt to regulate the interaction between robots and humans in the workplace. For instance, the ISO 10218-1 (2011) and ISO 10218-2 (2011) standards contain the requirements for these interactions to minimize critical hazards. According to Martinetti et al., (2021), however, the focus on physical risks is often to the detriment of non-physical risks. To get a broader understanding of the robotics safety, there ought to be a collective

effort between experts in industry, academia, and research organisations to develop a comprehensive body of knowledge on the safety risks in this unique but evolving sector (Martinetti et al., 2021). Workers may suffer from mental stress due to the presence of robots in the workplace for various reasons (Jones, 2017; Mercader Uguina and Muñoz Ruiz, 2019). Thus, there is a changing paradigm that influences the safety risk factors beyond the physical risks.

Methodology

In order to address the aim of this study, desk research accompanied by two expert workshop discussions, was used to (1) establish the most widely used construction robots and (2) identify safety risks factors associated with their use in construction. This was achieved through a detailed review of safety requirements for each equipment type identified through the desk research. Desk research is a secondary research method that primarily involves the collation and synthesis of data in published or unpublished but relevant documents. The desk research followed structured review steps proposed by O'Leary (2014) for secondary research. Following recommendations on good sources for secondary data analysis (Manu et al., 2021), the following documents were reviewed: operation manuals, standards, trade and industry publications, academic literature, and web materials. The desk study was broken into four streams with each led by an experienced professional with an average of 15 years' experience in the areas of construction, robotics, and automation as well as health and safety.

The expert workshop followed the focus group discussion (FGD) format. This process allowed experts to present results from each of the four desk studies and discuss in detail safety risk factors associated with the use of the various types of construction robots. The FGD format also aided the exploration of expert views on the categorisation of several types of construction robots and robotic devices for the purposes of analysing the safety risk associated with them. Two workshops were conducted with 12 and 9 participants, respectively. Experts had over 10 years' experience each in a related subject and comprised of civil engineers, robotics and automation researchers, surveyors and construction lecturers and trainers. Purposive sampling techniques were employed to recruit experts with requisite knowledge on the subject given its relative novelty in the construction sector. The participants were recruited from a as part of a broader project on construction robotics and automation safety thus involved participants with requisite knowledge and interest in the subject area. The high level of expertise and interest makes FGD discussions richer and more valid (Creswell, 2013). FGDs normally involve a small group of participants to ensure effective management of the data (Polkinghorne, 1989). FGD group methods aid interrogation of the phenomenon to high levels of detail and depth while reducing primary researcher bias or omissions (Creswell, 2013). This approach helped to provide the most comprehensive list of safety risk factors as well as compare safety risks across different automation and robotics contexts for construction. The FGD was adopted to allow the participants to draw from each other's desk research and compare notes in order to compile a more concise but comprehensive list of safety risk factors. In combining the desk study and workshop discussion findings, a detailed thematic analysis was used to synthesise the risks into appropriately categorised set of risks based on the sources of these risks. The thematic analysis followed qualitative data analysis structure with coding (see Creswell, 2013) developed with reference to suggested list of risk sources during FGDs.

Findings

The primary aim was to identify safety risk factors associated with use of construction robots as well as ascertain the sources of these risk. From the desk study, several categories of construction robots were identified. Some of the robots are widely used (e.g. demolition robots), while others are less common (e.g. bricklaying robots). The list of construction robots identified in the desk study were categorised as follows: Autonomous aerial robots, Autonomous terrestrial transport robots, Autonomous and mobile construction equipment, Fixed construction robots (onsite/offsite), wearable construction robots and collaborative construction robots. Robots under each category were identified and listed. For each of the listed robots a list of safety requirements

was generated through review of manufacturers’ publications, specifications, manuals, and academic articles. This was then used as basis for focus group discussions with experts to outline safety risk factors that may influence their use in the construction context. The safety risk factors synthesised into a concise list of 59 after systematic probing, coding and thematic analysis and elimination of duplicates. The thematic analysis was performed to primarily identify the sources safety risks leading to the identification of 8 main themes: (1) Human issues, (2) Control issues, (3) Mechanical failure, (4) Robot design failure, (5) Robot installation failure, (6) Work design failure, (7) Procedural failure, and (8) Environmental issues. These 8 themes were further categorised into three primary risk source categories namely robot, work environment and operation/operator. The detailed list of the risk factors identified in the desk research and thematic mapping to risk sources has been presented in Table 1. From this analysis, the work environment (work design and procedural failure) can be considered a source of the majority of risks followed by issues related to the robot itself (Control issues, mechanical failure and installation failure) and finally issues related to operation/operator (human issues). Whereas most risks identified pertain to physical risks from interaction some interesting non-physical risks were also identified, including psychological and cognitive issues associated with working with robotic.

Table 1: Safety Risk Factors in the Use of Construction Robots

Risk Factors	Key Sources of Risks							
	Human Error	Control Issues	Mechanical Failure	Robot Design Failure	Robot Installation Failure	Work design Failure	Procedural Failure	Environmental Issues
Lack of warning signals and signs	•	•	•	•	•	•	•	•
Unintentional movement of robot parts	•	•	•	•	•			
Fall of robot parts	•	•			•			
Contact (with robots and robot parts)	•	•	•	•		•	•	
Flying substances and objects from the operations				•		•	•	•
Explosions			•		•			•
Worker falling-off robot	•					•	•	
Workers being run over	•					•	•	
Lack of separation of robot (from workers or environment)						•	•	
Lack of safety perimeter						•	•	
Lack of safeguarding						•	•	
Particles and debris release				•	•	•	•	
Building part collapse due to robotic operations						•	•	•
Electrical and electrocution	•		•		•		•	•
Inhalation of dangerous substances (Dust, Chemical, Fumes, Gas etc)			•	•	•	•	•	
Overworking humans who work with robots	•					•		
Noise			•	•	•	•		
Vibrations			•	•	•	•		
Worker distraction	•					•	•	
Poor travel or route planning						•		
Unsuitable terrain for robot						•	•	
Poor visibility of robot						•	•	•
Poor robot warning indication								
Robot malfunction		•	•	•	•			
Loss of control of robot		•						
Unsuitable weather conditions						•		•
Presence of unwanted third party e.g. animals						•	•	•
Fire hazard	•	•	•	•	•	•	•	•
Failure of robot control system		•	•					
Incorrect use of robots	•					•	•	
Manual handling and lifting	•					•	•	
Non-use of correct PPE for robot	•					•	•	
Robot collapse		•	•	•	•			
Unplanned movement of robot		•	•					
Overturning robots		•	•			•		
Explosion risks			•	•				
Obstacles for robot						•	•	•
Loss of concentration of operators	•					•	•	•
Loss of concentration of workers	•					•	•	
Poor work environment safety planning						•	•	
Non-adherence to safety procedure	•					•	•	
Lack of safety warning on site	•					•	•	
Lack safety warning on robot				•		•	•	
Lack of instructions				•	•	•	•	

Lack of training							•	•	
Weight and lack of consideration of load bearing capacity of structures							•	•	
Poor house-keeping in environment	•						•	•	
Collision with other equipment	•						•	•	
Collision with building elements	•						•	•	
Contact with hot parts or substances	•			•			•	•	
Lack of risk assessment							•	•	
Ineffective robot warning system				•			•	•	•
Physical interference with robot							•	•	
Unauthorised access	•						•	•	
Lack of protocols and policy								•	
Ergonomic risks	•			•			•	•	
Lack of safety standards								•	
Poor knowledge of robotics safety in construction	•						•	•	
Psychological, mental and cognitive issues	•						•	•	

The thematic mapping of the risk factors to each source of risk was performed. Then a summation of the number of factors associated with each source ascertained. From this analysis it was found that most risks are associated with work design and procedural failures, followed by human issues and robot design failures. This is presented in Figure 1. This does not, however, indicate the likelihood of occurrence or impact. This primarily outlines the number of identified safety risk factors that are associated with the risk source. Subsequent research will examine prevalence, the likelihood of occurrence and impact.

<insert Figure 1 here>

Figure 1: Sources of Construction Robotics Health and Safety Risks

The lists of risks per equipment-type was also summarised and analysed. From the analysis, Autonomous aerial robots, Autonomous terrestrial transport robots and Autonomous and mobile construction equipment were found to be more prone to Procedural Failure and Environmental Issues. Fixed construction robots (onsite/offsite) were found to be more prone to robot design failure, robot installation failure, work design failure and procedural failure. Wearable robots are more prone to robot design failure while collaborative robots are more prone to procedural failure. All equipment types are however equally prone to human issues and other mechanical failures. This is summarised in Table 2.

Table 2: Categorisation of Construction Robotics and Key Sources of Safety Risk

Categorisation of Construction Robotic Equipment	Examples	Applicable Risk Sources*							
		1	2	3	4	5	6	7	8
Autonomous aerial robots	Unmanned Aerial Vehicles, (uses including surveying, transport, inspection and scanning)	•	•	•	•	•	•	••	••
Autonomous terrestrial transport robots	Autonomous site transport vehicles, dumpers and dump trucks; main uses for transport of workers, materials and equipment	•	•	•	•	•	•	••	••
Autonomous and mobile construction equipment	Autonomous glass fixers, diggers, welders, power floats, bricklayers, painters and sprayers, pavers, rendering machine, and earthmoving equipment (excavator, dozer etc) and demolition robots, mobile 3D printers and extruders, self-assembly formwork; rail sleeper layers etc	•	•	•	•	•	•	••	••
Fixed construction robots (onsite/offsite)	3D printers, Computer numerical (CNC) machines. concrete extruders; factory equipment for various tasks (cutting, welding, grinding,	•	•	•	••	••	••	••	•

	profiling, etc) especially in offsite manufacturing								
Wearable construction robots	Exoskeletons	•	•	•	••	•	•	•	•
Collaborative construction robots	Robot dogs, small autonomous worker assistant devices	•	•	•	•	•	•	••	•

*1. Human Issues; 2. Control issues; 3. Mechanical failure; 4. Robot Design Failure; 5. Robot Installation failure; 6. Work design Failure; 7. Procedural Failure; and 8. Environmental Issues;

• - indicates risk applicable; •• - denotes predominant risk for a particular type of equipment

Discussion

An effective categorisation of construction robots for the purposes of identifying safety risks has been proposed. The categorisation is based on the core mechanical characteristics of the equipment particularly in relation to mode of movement and approach of interaction with users/operators. This accords with Ben-Ari and Mondada (2018) prescriptions how robots can be categorised. The categories are Autonomous aerial robots; Autonomous terrestrial transport robots; Autonomous and mobile construction equipment; Fixed construction robots (onsite/offsite); wearable construction robots and collaborative construction robots. This categorisation is significantly different from previous categorisations of construction robots as these previous studies (e.g., Delgado et al., 2019) did not necessarily separate robots on the basis of mobility. The categorisation in this study however acknowledges this as more relevant in the context of safety.

Robotics safety has often been viewed from the perspective of physical safety emanating from the interaction between humans and machines (Vasic and Billard, 2013). Thus, most standards and directives on robotics or automation safety have focussed on the separation of humans from machines (Martinetti et al 2021). Furthermore, robotics implementations within construction will most likely be hybrid where machines will interact with human workers. Thus, these developments have influenced views in construction robotics safety discourse. However, current developments in robotics have evolved beyond mere physical artefacts and their manipulation but now involves other dimensions interaction including non-physical interaction. There are therefore emergent risks beyond physical safety (see Jones 2017), which includes the psychological and mental impact of working with machines. Thus, the identification of risks such as physiological and mental strain accord with studies such as Martinetti et al (2021) who have highlighted the problem of non-physical risks. It emerged from the desk research and FGDs that accidents and ill health could increase when humans try to match the efficiency of robots. Other risks may relate to challenges and frustrations when humans try to match robot efficiency. Furthermore, communication with machines that incorporate conversational intelligence and voice interactivity could sometimes be frustrating and affect workers wellbeing. Despite these areas of emerging risks, the majority of risk factors outlined still relate to physical safety risks. It is also worth noting that a significant amount of the risks identified are similar to risks that affect traditional construction thus familiar to construction safety managers. For example, four of the five top causes of fatalities in UK construction were also identified as risks in construction robot use (i.e. trapped by collapsing objects, being struck by moving objects, being struck by moving vehicles, and electrocution) (HSE 2020). This work also highlights the fact that although robots can be designed to be inherently safe, there are residual safety risk that relate to the work environment and most importantly human issues that are more difficult to design-out. Thus, this highlights the continued importance of training. The study also highlights the need for an expansion of the remits of regulations and standards to consider non-physical risks including psychosocial risks factors and their mitigation.

Implications for Practice

This study outlines safety risk factors in construction robotics through a comprehensive list of risks as well as their sources. This list can help in risk assessments and the identification of knowledge areas for safety training in construction robotics scenarios. From this list, safety risk situations can be modelled for the purposes of training including the use of Virtual Reality (VR) supported

training (e.g. Dianatfar et al., 2021). This has pedagogic value in the context of training with the over 50 risk factors which can be incorporated in the scenarios for training as well as assessment of knowledge. The generated list of risk factors as well as analysis of their sources can also help in the development of appropriate safety management manuals standards and programmes. This is even more important given that the development of safety standards for robotics is still evolving with no specific known standards for construction robot use.

Conclusions

The emergence of construction robots is envisaged to transform the industry, especially with great potential to improve performance. Despite the numerous benefits, however, it will influence the way construction is organised as well as ways of working. Initial models indicate a hybrid approach where robotics and human workers are likely to collaborate in close proximity. These interactions will invariably lead to some health and safety risks as well as accidents. This study thus examined risk factors associated common construction robots. The study adopted expert desk research and workshops. This led to the identification of 59 risks factors and 8 risk sources. The study highlights the dominance of physical risks over other risks but also highlights the emergence of psychosocial risks which are yet to be well understood as well as addressed by standards and regulations. The study highlights the importance of the risk sources and their role in the development of mitigation strategies including training which can be designed to improve perceptions and awareness of a variety of safety risk factors.

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References

- Asimov, I. (1984). *The Bicentennial Man*. Philosophy and Science Fiction (Philips, M., ed), pp. 183-216, Prometheus Books, Buffalo, NY.
- Bock, T. (2007). Construction robotics, *Autonomous Robots*. 22. 201–209 <https://doi.org/10.1007/s10514-006-9008-5>.
- Bock, T., Linner, T. and Ikeda, W. (2012). Exoskeleton and humanoid robotic technology in construction and built environment, *The Future of Humanoid Robots-Research and Applications*, InTech,.
- Bogue, R. (2018). What are the prospects for robots in the construction industry? *Ind. Robot An Int. J.* 45 1–6 <https://doi.org/10.1108/IR-11-2017-0194>
- Bowen, G. A. (2009). Document analysis as a qualitative research method. *Qualitative Research Journal*, 9(2), 27-40. doi:10.3316/QRJ0902027
- Cobb D. (1998). *Robobuild Report*, A report supported by the Institution of Civil Engineers Research and Development Enabling Fund and the Building Research Establishment Ltd.
- Creswell, J.W. (2013) *Qualitative Inquiry and Research Design: Choosing among Five Approaches*, 3rd ed.Sage Publications, London, 2013.
- Delgado, J. M. D., Oyedele, L., Ajayi, A., Akanbi, L. Akinade, O., Bilal, M. and Owolabi, H. (2019). Robotics and automated systems in construction: Understanding industry specific challenges for adoption. *Journal of Building Engineering*, 26.
- Dianatfar, M. and Latokartano, J. and Lanz, M. (2021) *Concept for Virtual Safety Training System for Human-Robot Collaboration*. 30th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2021) 15-18 June 2021, Athens, Greece.
- Directive 89/391/EC, of 12 June 1989 on the introduction of measures to encourage improvements in the safety and health of workers at work.

- Gharbia, M., Chang-Richards, A., Lu, Y., Zhong, R. Y. and Li, H. (2020) Robotic technologies for on-site building construction: A systematic review. *Journal of Building Engineering*, 101584.
- Harper, C., and Virk, G. (2010). Towards the Development of International Safety Standards for Human Robot Interaction. *Int J of Soc Robotics* 2 (3), 229–234. doi:10.1007/s12369-010-0051-1
- ISO 10218 “Robots and robotic devices – Safety requirements for industrial robots”, with parts 1 (“Robots”) and 2 (“Robot systems and integration”), ISO Copyright Office, Geneva, 2011.
- Jansen, A., van der Beek, D., Cremers, A., Neerincx, M., and van Middelaar, J. (2018). Emergent Risks To Workplace Safety; Working in the Same Space As a Cobot.
- Jones, D. R. (2017) Psychosocial Aspects of New Technology Implementation. *International Conference on Applied Human Factors and Ergonomics* (Cham: Springer), 3–8. doi:10.1007/978-3-319-60828-0_1
- Kaamin, M., Razali, S.N.M., Ahmad, N.F.A., Bukari, S.M., Ngadiman, N., Kadir, A.A. and Hamid, N.B., (2017). The application of micro UAV in construction project. In *AIP Conference Proceedings* (Vol. 1891, No. 1, p. 020070). AIP Publishing LLC.
- Martinetti A, Chemweno PK, Nizamis K and Fosch-Villaronga E (2021) Redefining Safety in Light of Human Robot Interaction: A Critical Review of Current Standards and Regulations. *Front. Chem. Eng.* 3:666237. doi: 10.3389/fceng.2021.666237
- Mckinsey & Company, Improving construction productivity. <https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/improving-construction-productivity>, 2017 [Accessed Web Page].
- Mercader Uguina, J.R. and Muñoz Ruiz, A.B. (2019). Robotics and Health and Safety at Work. *International Journal of Swarm Intelligence and Evolutionary Computation*. Vol. 8 Iss. 1 No: 176
- O’Leary, Z. (2014). *The essential guide to doing your research project* (2nd ed.). Thousand Oaks, CA: SAGE Publications, Inc
- Polkinghorne, D.E. (1989) Phenomenological research methods, in *Existential-phenomenological perspectives in psychology*, Springer, 1989, pp. 41–60.
- Rubio, F., Valero F. and Llopis-Albert, C. (2019) A review of mobile robots: Concepts, methods, theoretical framework, and applications. *International Journal of Advanced Robotic Systems*. doi:10.1177/1729881419839596
- Soffar H. (2019) Automation, Industrial Robots types and importance. Available from: <https://www.online-sciences.com/robotics/automation-industrial-robots-types-importance-cartesian-scaras-robots-cylindrical-parallel-delta-polar-and-articulated-robots>
- Taylor, M., Wamuziri, S. and Smith, I., (2003), February. Automated construction in Japan. In *Proceedings of the Institution of Civil Engineers-Civil Engineering* (Vol. 156, No. 1, pp. 34-41). Thomas Telford Ltd.
- Torku, A., Bayrak, T., Ogunlana, S.O., Chan, A.P.C. and Owusu-Manu, D.G. (2021). Are the Ageing Workforce Satisfied with the Construction Work Environment? In *Collaboration and Integration in Construction, Engineering, Management and Technology* (pp. 101-106). Springer, Cham.
- Trujillo, D.J. (2020). Barriers to Automation and Robotics in Construction. *EPiC Series in Built Environment*. Vol 1, pp.257–265.
- Vasic, M. and Billard, A. (2013). Safety Issues in Human-Robot Interactions. 2013 IEEE International Conference on Robotics and Automation (ICRA). Karlsruhe, Germany.
- You, S., Kim, J., Lee, S., Kamat, V. and Robert Jr., L.P. (2018) Enhancing perceived safety in human–robot collaborative construction using immersive virtual environments. *Automation in Construction*. 96, 161–170.
- Zhang, X., Li, M., Lim, J.H., Weng, Y., Tay, Y.W.D., Pham, H., Pham, Q.C., (2018). Large-scale 3D printing by a team of mobile robots. *Automation Constr.* 95, 98–106. <https://doi.org/10.1016/j.autcon.2018.08.004>

