Parallel Kinematic Construction Robot for AEC Industry

M. Klöckner[a], M. Haage[a], K. Nilsson [b], A. Robertsson[c], R. Andersson[d]

[a]Department of Computer Science, Lund University, Sweden
[b]Cognibotics AB, Lund, Sweden
[c]Department of Automatic Control, Lund University, Sweden
[d]AChoice AB, Malmö, Sweden

E-mail: maike.klockner@cs.lth.se, mathias.haage@cs.lth.se, klas@cognibotics.com, anders.robertsson@control.lth.se, ronny.andersson@achoice.se

Abstract –

This article reports work-in-progress of a parallel kinematic robot development for construction with main focus on the concept phase. We assume the weight distribution of the proposed structure enables integration of robotic components into construction equipment while enabling tailoring of important characteristics such as accuracy, stiffness and workspace toward application needs. We describe challenges as well as kinematics, simulation and an experimental setup for evaluating performance of the proposed concept in a construction experiment using a concrete build system.

Keywords –

Parallel kinematic manipulator; Construction robotics; Concrete build system

1 Introduction/preliminary work

The community building sector in Sweden has an annual turnover of around SEK 500bn with 500,000 employees in 20,000 companies. However, productivity development is very low and has been for a long time. Low profitability and the absence of strong drivers of change are preserving the sector. For instance, in mass production of reinforcement, plasterboard, insulation, steel profiles and concrete, one person hour produces material for more than 50 m² of exterior wall with high profitability. At the same time experience show that for finished (built) exterior walls, one person hour has often only produced less than 1 m², this independent of construction material, whether, prefabricated or site-built. Swedish and international efforts to improve productivity in construction have often landed in prefabrication of composite components and building information modeling (BIM). However, the success of trying to increase productivity and profitability through this approach has been limited, mainly due to compound product complexity, inability to handle variations in deliveries, high fixed services and best widespread fragmentation in a project-based construction process [1].

In the manufacturing industry, customer focus, digitization and use of robots enabled mass customization and increased productivity. However, in the construction sector, the degree of automation is very small and in principle none of the players work with flexible customer-based production. Investments have been made but large-scale solutions have failed. The utilization of robots in the construction sector is limited by adaptation to the construction site, rapid and agile change of work steps and that the sector needs a balanced and small-scale collaboration between man and machine at the construction site. Today, the construction sector has about 3 times the number of accidents and load-related illnesses compared to other operations in Sweden, and the situation makes it difficult to improve the working environment and safety as well as to reduce both climate and environmental impact. Recent literature surveys support these findings and list hampering factors such as lack of interoperability, tolerance management, experts, power and communications as well as design for human installation procedures, high initial investment and risk for subcontractors, immature technology, unproven effectiveness, and low R&D budgets, among others [2, 3, 4]. At the same time, there are indications that automation is needed in AEC for continued growth [5].

To target these issues at a national level a Swedish center for construction robotics [1] is being formed in collaboration with the Swedish concrete industry. The center aims to develop, adapt and demonstrate automation solutions for construction before being put to use at construction sites, and act as a knowledge

[1] Swedish national center for construction robotics, http://www.lth.se/digitalth/byggrobotik/

transfer channel from academia to Swedish industry within construction robotics. Efforts now being carried out in associated national research projects aims to demonstrate a feasible automated construction system for small concrete house production in Sweden. The hypothesis is that the use of small-scale robotics gives feasible construction automation. Two robot automation approaches are being tested: utilization of off-the-shelf industrial robot arms from the manufacturing industry for automation of in-situ processes, and utilization of parallel kinematic manipulators (PKMs) for use in-situ and for prefabrication processes.

The type of PKMs put forward in this article fit, in our opinion, well for automation of construction tasks. The weight distribution of the robot with mass concentrated to stationary parts suits well for integration into construction equipment. Corresponding light-weight arm systems can be tailored toward processes in important robot characteristics such as accuracy, stiffness, and workspace.

This article describes our experimental setup and motivation behind selection of the two robot types as candidates for construction work, as well as reporting work-in-progress regarding development of PKMs for construction. The rest of the article is outlined as follows: a test process is described (masonry using the Finja Exakt build system[2]). This is followed by a short description of the off-the-shelf robot system (important as we plan for comparison of performance between the systems). Then a general overview of parallel kinematic manipulators is given to illustrate the machine concept, followed by work-in-progress reporting on initial steps we needed for adaptation to construction experiments. Currently open problems regarding integration, safety and interaction are then discussed briefly. Last, future work and current conclusions end the article.

2 Masonry process

The targets for experiments in current projects are processes needed for small concrete house construction, such as shown in Figure 1.

This particular house type is constructed using a build system based on a refined type of concrete blocks. The process of placing the blocks to form the outer walls is not that time consuming (about two days manual labor by two persons), but it is heavy and non-ergonomic work involving a total lifting of several tons of material during short time. Fully or partially replacing manual labor in this specific process would remove a strenuous work task. From a robot automation point-of-view the process contains most challenges that need to be addressed for robot application on-site, such as safety, calibration, performance, workspace, etc. Furthermore, commercial automation solutions exist (HadrianX [6], SAM100 [7]) as well as research prototypes (in-situ fabricator [8,9]) for benchmarking and comparisons.

Figure 1. House type targeted for masonry robot automation

2.1 Manual masonry process

The Finja Exakt system consists of a family of insulated blocks that are available on pallets of around 40 blocks per pallet. The system consists of a number of blocks to handle different situations such as corners, windows and doors. The weight of individual blocks vary between 15 and 20 kg. Blocks are stacked in layers of 200 mm including a 3 mm thin layer of Exakt mortar, with possibility of a half layer of 100 mm. The length of an individual block is around 600 mm. The Exakt system exists in three different widths, 290, 350 and 400 mm. We limit ourselves to consider only the 350 mm width for experiments.

The manual process is specified in Finja Exakt manuals[3]. The steps involved are visualized in Figure 2; starting from a slab and a blueprint, the first layer of blocks is layed down with care taken to accurate placement of openings and care taken to achieve an even layer height. Mortar is applied using a special tool for application (white box). Every few layers (not each layer) reinforcement is applied. Custom block sizes needed for corners and openings (windows and doors), are solved by on-site sawing of blocks, see Figure 3.

[2] Finja Exakt system, https://youtu.be/S6NdghrdLkI

[3] Finja Exakt build system manuals (see link “arbetsanvisning” (Swedish for work manual), https://www.finja.se/produkter/block/isolerblock-exakt?id=16292060

Figure 2. Steps in the masonry process with Finja Exakt block system; first layer (top left), application of mortar (top right), application of reinforcement (bottom left) and customization for cabling (bottom right).

Figure 3. Finja Exakt Block with corner block (left) and on-site customization of sawing block (right).

3 Research contribution

Within this paper we show our recent work-in-progress towards building a construction robotics lab including a PKM and an industrial arm robot to explore robotic aspects of construction processes. Our main contribution belongs to the development of the PKM and to the final development of the process customized industrial arm robot for construction tasks. Next to the robot development our contributions comprise in investigating application aspects of construction processes. These aspects include e.g., logistics, material flow, safety, collaboration, and risks. The first process we explore the mentioned aspects for is masonry.

4 Industrial construction robot

Industrial robot arms were originally developed for long series manufacturing, typically batch production in automobile industry, with the robot specializing in dirty and dangerous processes, such as welding and painting, as well as highly repetitious tasks such as pick- and place operations. The main important characteristics being high repeatability and low cycle time. An industrial robot is typically placed in a well-organized cell within a production line. In construction the most similar environment is in prefabrication where similar thinking may apply, though with different materials. Prefab wood house production already has automation solutions involving robotics. For prefab concrete the main application so far seems to be 3D printing, but then featuring large Gantry structures built to scale. For on-site production there are several factors to consider:

The environment is less structured than in a traditional robot cell, furthermore it may be unique for each new construction site. Figure 4 shows a typical small house slab cramped with construction material and cabling.

In the construction context considered, adoption to the blueprint typically happens at centimeter tolerance. Blocks are also allowed a few millimeters of placement tolerance since a grouting process evens out small errors. Accumulation of errors are not tolerated. On-site robot systems need efficient on-site calibration methods and/or accurate positioning sensing.

Mobility is probably required unless prefabrication on-site is sufficient (it very well may be) since the house is much larger than the workspace of the typical robot arm. In such case, the form factor of the robot and mobile platform should fit standard openings in the construction and adhere to pressure limitations posed by slab or use workarounds such as distributed steel plates. A small form factor also needs to ensure stability to allow utilization of robot performance.

Figure 4. Typical small house slab cramped with construction material and cabling

The protection class of the robot system needs to handle the on-site conditions, which includes abrasive materials and weather conditions. Most current industrial robot brands are available in IP67 editions which however is not enough leading to the need for protective clothing.

Opposed to manipulating a material flow through a cell, the robot system needs to adopt to the less structured material logistics on the construction site, or to enforce more structure to suit the automation process.

Safety, interaction and collaboration are important subjects. They are therefore given a separate section later in this paper.

The concept to be tried out is integration of an off-the-shelf industrial robot arm with an off-the-shelf piece of construction equipment as mobile platform, similar to what is seen recently in literature (the in-situ fabricator). Unlike the fabricator we will put focus on integration of the robot system into an automation system including considerations for the build system used. The system will be used for comparison with the PKM robot described next.

5 Parallel kinematic machines (PKMs)

Parallel kinematic machines (PKMs), classified as robots whose arms have concurrent prismatic or rotary joints in so-called closed kinematic loops, differ from the standard serial manipulators in several important aspects and complementary broadens the applicability and use of robots [10]. With a significantly higher stiffness in relation to the inertia/moving mass, PKMs typically either show up in (I) industrial pick-and-place systems where the very high accelerations due low moving mass – for so called delta and cable robots the actuators could be mounted in the stationary frame and thus get low moving mass – one gets significantly shortened cycle times in comparison to what is achievable with serial manipulators at the corresponding energy budget. or (II) are used in industrial applications where the high stiffness and/or positioning accuracy are required; different machining operations such as grinding, deburring and cutting, where structures like Stewart-Gough platforms or different gantry manipulators provide beneficial configurations. Parallel kinematic structures are also quite common in active or passive fixtures. Cable driven robots have emerged during the last decade and one can find examples from suspended camera system in sport stadiums to large wire robots in industrial settings [11]. An often-advocated shortcoming of PKMs is the smaller workspace with respect to the footprint of the robot, compared to the typical serial manipulators, and the risk of collisions between PKM-links/cables and obstacles within the workspace. However, whereas this may be true in many industrial applications, the masonry of walls is a task where the workspace is very suitably tailored to a new PKM structure. Furthermore, the strength, stiffness, and positional accuracy of the PKM within this workspace makes it a competitive alternative. The Gantry-Tau PKM was developed for achieving a large, open workspace for structures in e.g., the aerospace and windmill industry where the reconfigurability concept encompassed and integrated calibration as important part of the concept [12]. Further development of the latter PKM-concept is an important step towards efficient use in AEC applications.

5.1 PKM for masonry

Here we present work-in-progress to adapt a PKM structure to automate the selected masonry process (see Chapter 2.1). Our work so far considers kinematic aspects (e.g. workspace, stiffness) and mechanical aspects (e.g. joints, drive concepts) as well as guidelines and standards relevant for collaborative robots [12, 13, 14]. The lab sized PKM is part of the experimental setup we build (Figure 5).

The work scenario contains: the PKM placed parallel to the wall we want to build at some distance from the wall. The end effector will be utilized for pick and place of blocks. Our first experiment will include pick and place of blocks with no humans in the robot cell with no collaboration taking place. Since we need Exakt mortar as a first layer a human will applicate one layer of Exakt mortar while the robot stops completely. Thereafter the robot will pick a block from a palette and place it at the needed position for building a wall. After placing one layer of blocks the robot stops again and the human applicates the next layer of Exakt mortar. As a next step the robot starts to perform pick and placement of next block layer and so on. Parallel to these experiments we will perform experiments with the industrial construction robot with regard to automated

Exakt mortar application which will be later adapted into the PKM experiments.

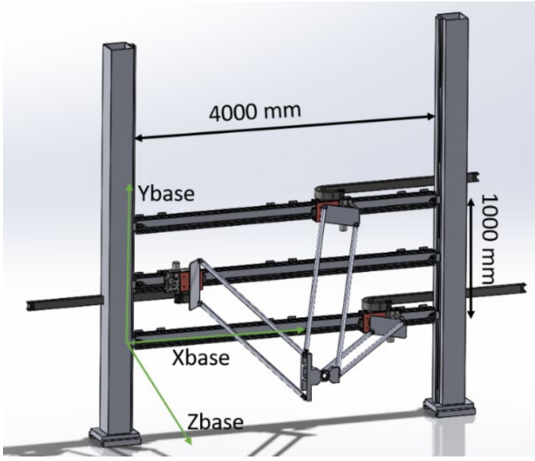

Figure 5. CAD of lab sized PKM with coordination system and wrist dummy

PKM development has so far been divided into four main parts. At a first step we investigate the basic PKM mechanism and structure to realize the translatory movement (basic PKM - translatory movement). In a second step we investigate the wrist, the end effector and the drive concept for the end effector to realize the rotatory movement with modular parts, adaptable for different applications (advanced PKM - rotatory movement). In a third step we have to investigate movable support structure to bring our PKM in a full sized version to the construction side or other relevant application places (support structure). The fourth step includes implementation of safety and interaction for human robot collaboration. This division into four parts (translatory movement, rotatory movement, support structure, safety and interaction) is very important since our aim is to bring the PKM into different application areas with different human robot interaction levels. Further explanations contain the PKM development regarding the translatory movement and the implementation of safety and collaboration.

5.2 Basic PKM – translatory movement

The basic PKM for construction tasks (Figure 6) consists of three kinematic chains. Each chain includes an actuator, which is realized by motor driven carts moving on tracks. A total of six links is used. These links have fixed length and are connected to the carts and the wrist in a 2-2-2 configuration. Joints used for the connections are at this stage spherical joints with a tilting angle of +/-45 deg. Two of the carts are placed on one side and the third cart is placed on the other side in comparison to the wrist. By this configuration we are already able to realize the three translatory degrees of freedom (DOF). The wrist itself consists of a support platform, where the fixed length links are connected to and of a tool platform with which we realize the rotational DOFs.

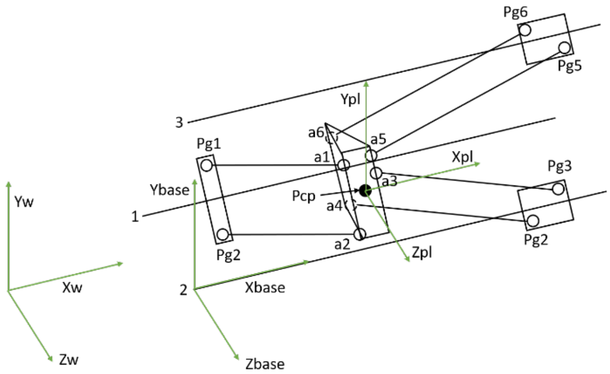

Figure 6. Schematic construction PKM for translatory movement with notation for variables and parameters

Since the wrist transmits the translatory movement and realizes the rotational DOF it has a key function in our PKM. Furthermore, the chosen connection points from links and wrist have a high impact on stiffness. The best regarding stiffness is to choose the distances between the links as big as possible.

For figuring out the best combination of distances between tracks, length of links and distances between links in dependency of workspace we realized the kinematic modeling. The kinematic model contains a defined cubic workspace in which we proof the reachability of the platform center point (Pcp). Further we described the inverse kinematics from Pcp over connections links/wrist (a1, a2, …, a6) to connection links/carts (Pg1, Pg2, …, Pg6) to carts. After this we calculated the intersection points of the links with the tracks to check if there are intersection points in the defined areas along x-axis. In case of intersection points we had to figure out which of the intersection points are valid. Moreover, we had to proof the angles between the links and the wrist and the links and the carts. We did this because we used spherical joints with +/- 45 deg tilting angle. After this procedure we found out which points in space are reachable with our configuration. Figure 7 shows reachable workspace in green for a PKM with 4000 mm tracks, 500 mm distances between tracks in y-direction, length links 2 and 3 = 1722 mm, length links 1 = 1648 mm. With this configuration it will be possible to build a wall with length = 1,8 m and height = 1,5 m which will be appropriate for our experimental setup. For later use of the PKM on the construction site calculations will be adapted to design an upscaled version.

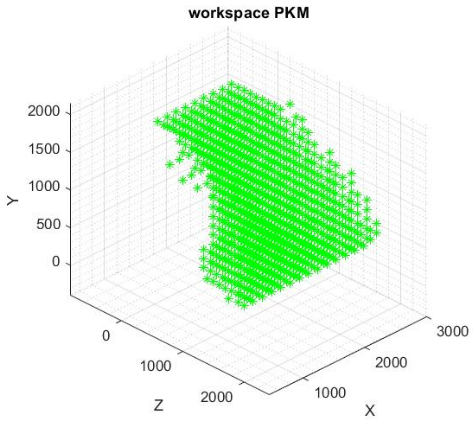

Figure 7. Result workspace calculation – Reachable points in space of platform center point for translatory movement

Due to the fact, that we want to perform first experiments to evaluate stiffness, torsion and workspace with the calculated parameters, we decided to build a downscaled version with parts to realize translatory movement (Figure 8).

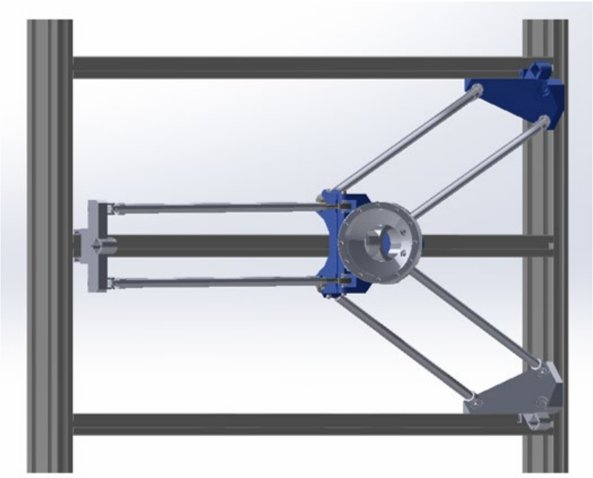

Figure 8. CAD PKM – designed for downscaled version

To fasten up the mentioned process, we designed the downscaled version of the PKM for first experiments with 3D-printed and out-off the shelf made parts and a functional support structure (Figure 9).

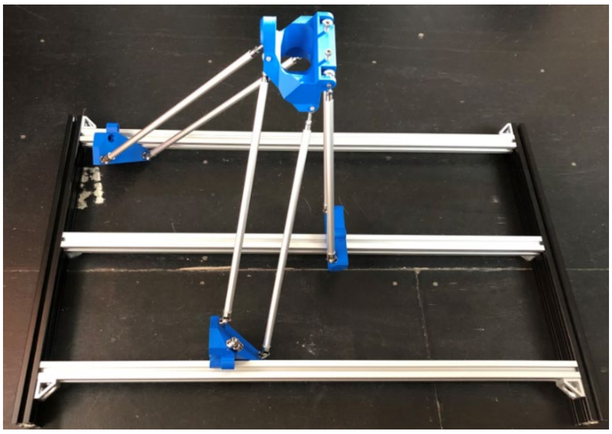

Figure 9. Realized downscaled PKM with 3 DOF

6 Experimental setup

Our experimental setup in the construction lab will contain the PKM placed parallel to the wall to build as well as a palette of blocks with the aim to perform pick and place experiments of blocks (Figure 10). Not shown in the picture, but planned, is the industrial arm application on the opposite side of the wall to perform experiments regarding pick and place, gluing and sensor integration. Since safety and interaction will be needed already in the lab, we will start to integrate some safety features in the shown application, which is described in the next chapter.

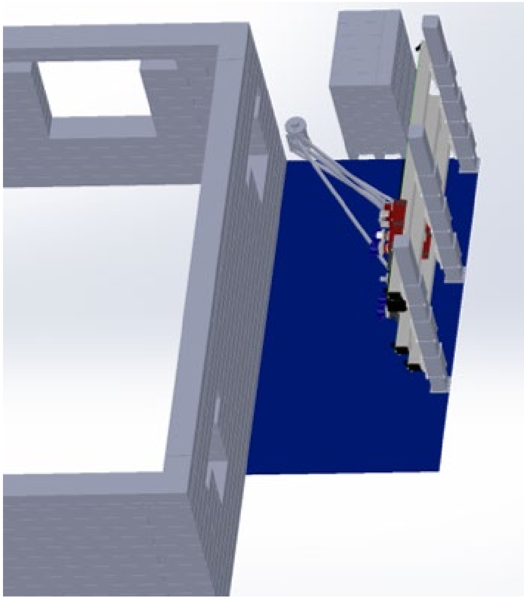

Figure 10. Experimental setup for PKM

6.1 Safety & interaction

The machine directive needs machines to fulfill stated requirements before they are considered safe for use. Traditional industrial robot cells disallow human presence during autonomous operation and ensure this situation by surrounding the cell with safety systems. Another approach is represented by collaborative robots where a limit in allowable utilized energy allow humans to work in close collaboration with the machine despite autonomous operation. The unstructured and perhaps changing environment on the construction site pose challenges for safe autonomous robot automation.

How can and must safety look like on construction site? Different approaches:

- Physical protection
- Disallowing human presence
- Supervised operation
- Detection of human presence

By limiting access to the robot structure itself by, for instance, providing an enclosure for the robot it is easier to limit access during operation. Approaches to small mobile robot factories often suggest enclosure of the robot in a container. Enclosing the entire work area (all or part of the construction site) for autonomous work provides safety by disallowing human presence altogether. Supervision of the operation at all times with personnel equipped with dead man's switch and emergency stops. Automatic detection techniques of human presence, such as laser planes. But this requires an uncluttered environment (no occlusions) for robust operation. There is no obvious option. This remains an open problem.

Another consideration is human interaction with the robot system. In a masonry automation system, examples could be refilling of mortar, requiring a human to get close to the robot system, or division of labor between a human and machine in the masonry process. These issues also remain open problems.

7 Future Work

Developing the drive concept for the wrist and the end effector as well as building the PKM in the lab. Part of the masonry process will be tested with the robot structure (the path for pick and place blocks). Moreover, we will carry out a feasibility study regarding the pick and place application of the blocks. Parallel to this realization we will create a simulation of the whole process. We will use this simulation to figure out cycle times in dependency of all process elements (robot, palette bricks, wall). Other work for next year contains implementing the gluing/cement application process as well as the needed hardware (pump, pipes, tool) for this process. We want to realize a tool changing system with which we can change between a gripper and a saw or a combination tool consisting of a gripper and a saw. We further need a block fixing station for sawing and a measuring system to define the needed length of the blocks before sawing. Another future process will be plastering.

8 Conclusion

With this paper we have shown work-in-progress of a parallel kinematic robot development for construction with main focus on the concept phase. There are many open questions and challenges remaining, some of them listed in this article. Robot challenges include large workspace, efficient calibration procedures, safety concepts, and human-machine interaction ability with regard to construction workers.

9 Acknowledgements

The authors gratefully acknowledge the support received from Boverket/"Innovativt Bostadsbyggande" (#6438/2018) and VINNOVA/"Innovativ Agile Construction for globally improved sustainability" (ACon 4.0 #2019-04750) as well as the support received from Robert Larsson (Cementa AB), Petra Jenning (Fojab), Cognibotics AB and Miklos Molnar (LTH). These projects provided the opportunity to investigate the use of parallel kinematic manipulators in construction applications and to develop a parallel kinematic manipulator for specific construction tasks.

References

[1] Aitchison M., Tabrizi T. B., Beim A., Couper R., Doe R., Engstrom D., ... & Nelson, J. *Prefab housing and the future of building: product to process*. Lund Humphries, 2018.

[2] Bock T. The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. *Automation in Construction*, 59, 113-121, 2015.

[3] Buchli J., Giftthaler M., Kumar N., Lussi M., Sandy T., Dörfler K., & Hack N. Digital in situ fabrication-Challenges and opportunities for robotic in situ fabrication in architecture, construction, and beyond. *Cement and Concrete Research*, 112, 66-75, 2018.

[4] Pivac M., & Pivac M. Fastbrick robotics. Online: https://www.fbr.com.au/, Accessed: 15/06/2020.

[5] Podkaminer N., & Peters L. Construction robotics, Online:https://www.construction-robotics.com/sam100/, Accessed: 15/06/2020.

[6] Sandy T., Giftthaler M., Dörfler K., Kohler M., & Buchli J. Autonomous Repositioning and Localization of an in situ Fabricator. *In Proceedings of the International Conference on Robotics and Automation*, pages 2852-2858, Stockholm, Sweden, 2016.

[7] Lussi M., Sandy T., Dörfler K., Hack N., Gramazio F., Kohler M., & Buchli J. Accurate and Adaptive In situ Fabrication of an Undulated Wall using On-Board Visual Sensing System. *In Proceedings of the International Conference on Robotics and Automation*, pages 3532-3539, Brisbane, Australia, 2018.

[8] Delgado J. M. D., Oyedele L., Ajayi A., Akanbi L., Akinade O., Bilal M., & Owolabi H. Robotics and automated systems in construction: Understanding industry-specific challenges for adoption. *Journal of Building Engineering*, *26*, 100868, 2019.

[9] Saidi K. S., Bock T., & Georgoulas C. Robotics in construction. In *Springer handbook of robotics* (pp. 1493-1520). Springer, Cham, 2016.

[10] Merlet J.P. *Parallel Robots,* 2nd ed. Springer Science & Business Media, 2006.

[11] ISO Robots and robotic devices - Collaborative robots. ISO 15066, 2016.

[12] ISO Safety of machinery – General principles for design – Risk assessment and risk reduction. ISO12100, 2010.

[13] ISO Safety of machinery – Safety-related parts of control systems – Part 1: General principles for design. ISO 13849-1, 2015.

[14] Pott A. *Cable-driven Parallel Robots: Theory and Applications,* Springer Berlin Heidelberg, 2018.

[15] Online: http://www.smerobot.org, Accessed: 15/06/2020.