Construction Robotics
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REVIEW

Insights into automation of construction process using parallel-kinematic manipulators

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Abstract
This article discusses challenges, experiences and lessons learned so far while transforming a masonry build system based mostly on manual labour into a robot automated build system. Our motivation for selection of this masonry process is to try out how robot automation could impact the architects in their design work by providing a tool to directly manipulate wall expression down to individual brick level. Such manipulation is often much too costly for manual labour today. Moreover, masonry is a challenging application to automate. Understanding the manual processes involved and transforming them into automation equivalents faces several challenges; among them handling and distribution of the different materials involved, selection of tooling, sensing for handling of variation and digital tooling for the programming of the process. A novel parallel-kinematic manipulator (PKM) with computerized numerical control (CNC) is used as target for experiments, because the performance properties in stiffness, workspace and accuracy will allow us to extend work into further construction processes involving heavy and dirty manual labour.

Keywords Construction robotics · Parallel-kinematic manipulator · Concrete build system

1 Introduction

Attempts at machines to perform automatic masonry have been tried from time to time. Even patents for bricklaying machines have been announced already in 1875 (Franke 1875). Despite this, bricklaying machines are not in common use today. There is one commercial machine available, the SAM100 (https://www.construction-robotics.com/sam-2/), offering automation of bricklaying for large straight building facades. Another commercial machine, Hadrian X (https://www.fbr.com.au/view/hadrian-x), is usually also mentioned but it uses a build system with much larger bricks. A recent online article called “Where are the robotic bricklayers” (Potter 2021) suggests several reasons why automation for masonry is not widely spread today. Among others, mortar is highlighted as a difficult material to handle whereby it is difficult to produce clean mortar joints, which also mirrors our experiences.

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In general, autonomous machines and robots are not common in the construction industry. Several articles investigate reasons why: (Saidi et al. 2016) lists lack of interoperability, design for human installation procedures, lack of tolerance management, power and communications as hampering factors. Buchli et al. (2018) and Delgado et al. (2019) list high initial investment and risk for subcontractors, immature technology, unproven effectiveness, lack of experts, low R&D budgets, among others. But there are indications that automation is needed in construction for continued growth (Bock 2015). Our interpretation is that digital, technical and regulatory infrastructure is lacking to lessen the effort of introducing autonomous construction machinery in the construction value chain. Furthermore, there is still no applicable performing strategy on how to decide in general which process steps of so far manual performed work are suited for automation processes and which process steps will be better performed manual. Moreover, the extraction of silent, i.e. undocumented, knowledge out of manual performed processes and transforming it into robot motions for the particular application is also still a big challenge. In the project, which this article is part of, we therefore work towards a model to bring business, technology and infrastructure together for bringing commercial application of autonomous robots and machinery closer to reality (ACon 4.0 (#2019-04750)). We also started up the Center for Construction Robotics (http://www.lth.se/digitalth/byggrobotik/) in 2018 as a forum between actors to meet and a test site for experiments on robot automation of construction processes.

The paper focuses on mapping the explained masonry process (Sect. 2) into robot equivalents, including adapting a new developed PKM for construction processes (Sect. 3), performing and discussing experiments (Sect. 4) as well as reflecting on the needed changes and decisions for transforming from manual labour into automation equivalents (Sect. 5).

2 Brick masonry fundamentals

The fundament on which our experimental setup is built on, from a masonry point of view, are bricks, mortar and process performance.

Bricks which are used in Sweden have different properties regarding dimensions, structure, surface, weight and colour. Most utilized in the Swedish construction business are standard sized bricks of the following dimensions:

- 250 × 120 × 62 [mm] (Swedish brick) (DIN EN 771-1 (2015)).
- 228 × 108 × 54 [mm] (Danish brick) (DIN EN 771-1 (2015)).
- 240 × 115 × 71 [mm] (German brick) (DIN 105 (2021)).

Bricks, independent of their size, are available as vertical coring brick, horizontal coring brick, solid brick, pre-wall solid brick and pre-wall vertical coring brick (https://www.lebensraum-ziegel.de/ziegellexikon/mauerziegel/allgemeine-definitionen-und-begriffe.html). Most available colours are yellowish, brownish, reddish and blackish. The surface itself is rough, sometimes sandy, corny or dusty and the weight of solid bricks is about 2000 kg/m^3 (DIN EN 771-1 (2015); DIN 105 (2021)), whereby single solid bricks of the sizes mentioned in the list above weigh between 1.3 and 2.0 kg.

Though there exist many different types of bricks with all their dissimilarities used in the construction industry, they have one thing in common: Deviations in their dimensions. We experienced up to +/−2.5 mm in width and height along their surfaces (see Fig. 1).

The brick type we focus on in our experimental setup is a red Danish brick with 228 × 108 × 54 [mm]. Next to the described deviations the brick contains the following characteristics: Red Danish bricks having an upper and a lower side and a front and a back. To achieve the best possible wall impression, it is important to arrange the bricks in the same orientation along a wall to build. Moreover, they have a solid body and have fine dust on their surfaces. These parameters

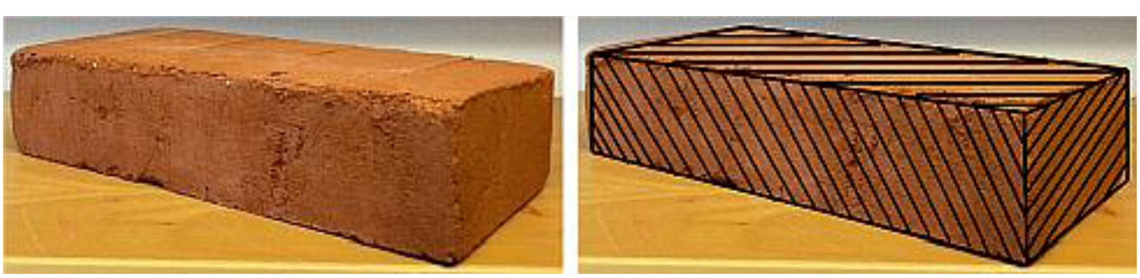

Fig. 1 Real brick with deviations (left) and ideal brick (right)

are very important for automation since they are influencing the tool design for handling the bricks as well as the choice of sensory instrumentation. A solid body brick can for instance be handled with vacuum technology whereas a hollow brick needs clamping technology to be handled. The current choice of sensory instrumentation utilizes point cloud information from consumer-grade RGBD-cameras, here used for proof-of-concept. The selected sensor, the Intel Realsense D435, features an adequate field of view (87 × 58 degrees) and near field distance of 28 cm. Depth accuracy is on the large side, around 10 mm close to near field distance. The measurement situation is therefore selected so that inaccuracies in depth can be compensated for by other means. In this case the image capture is always from above, so that depth inaccuracy translates to distance to brick surface inaccuracy. For pick operation, this in combination with a forgiving tool in depth direction. For placement and extrusion operations we rely on the robot absolute accuracy, around 0.4 mm. Given the specific measurement situation, the point cloud analysis method utilizes simple techniques such as depth thresholding and plane feature detection to extract pick points.

2.1 Manual brick masonry process

The manual masonry process for building a straight wall with bricks includes different action steps, logistics and use of special tools. To identify parts of the process appropriate for robot automation we analyzed this process in detail in a workshop with an expert mason. The process is divided into three main steps, including preparation, performance and post-processing. Sub-steps for the preparation include mixing of mortar, building a frame for building a leveled wall, putting a horizontal chord to define a specific height for each layer of mortar and bricks, brick- and tool supply. Sub-steps for post-processing includes grading vertical and horizontal joints, possible wall plastering and disassembly of framework.

For building a layer of bricks (process performance see Fig. 2) for a straight wall, we have set the horizontal stressed chord to a specific height. Thereby we defined a continuous height through all wall layers and achieved a regular build wall. For the application of bricks, we have put mortar with a defined dispersion on the prebuilt brick layer. The mortar was applied with a tool especially designed for the needed mortar dispersion (Fig. 3A) for the used sizes of bricks. Thereafter the brick was applied with a specific application strategy. This strategy contains tilting the brick behind the wall along its longitudinal and lateral axis (Fig. 3B and C), pushing it in this configuration on top of the mortar from the back of the wall, while tilting both axes back to “zero”. Thereby the current placed brick gets aligned along the former placed bricks (Fig. 3C and D).

Through this application technology a vertical joint between two side by side bricks as well as horizontal joints between bricks of two sequenced layers are generated. Furthermore, this application strategy offers us to control the flow of excess mortar whereby the joints become as clean as possible. To increase the walls stability vertical joints between bricks of two sequenced layers needs to be displaced. For the displacement we used normal, half sized bricks, which we generated by breaking them with a special hammer (see Fig. 4). Figure 2 also shows the backside of the wall, which was built in our workshop. To keep a nice impression on the front side, the mason pushed excess material towards the back side of the wall.

In general bricks are used both as facing bricks and bearing brick structure, i.e., a complete wall. The different

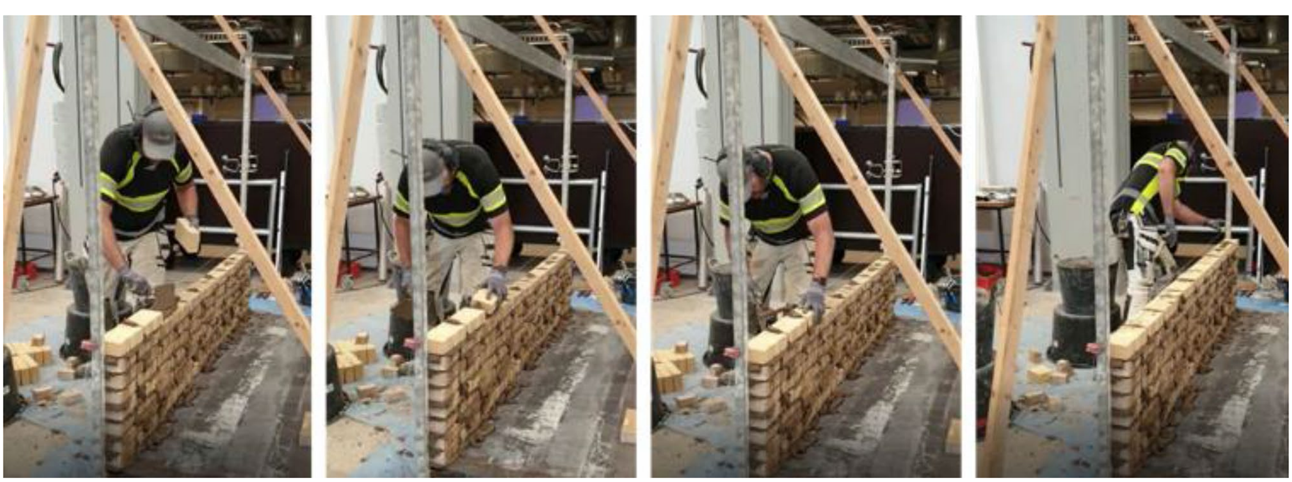

Fig. 2 Bricklaying: Apply mortar (left); disperse mortar with brick (middle left); push brick in position (middle right); set stressed chord for next layer (right)

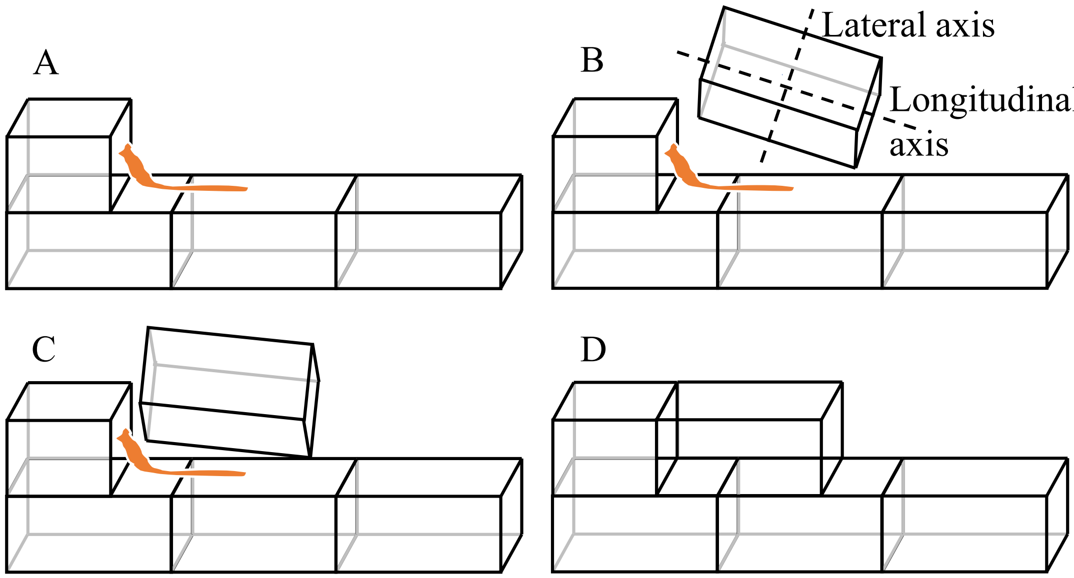

Fig. 3 Application strategy example for one brick using mortar (mortar dispersion = orange) and brick—front view. **A** Layer of bricks with applied mortar; **B** Rotation of brick on the way to application on mortar; **C** Rotation of brick shortly before application on mortar; **D** Applied brick on mortar

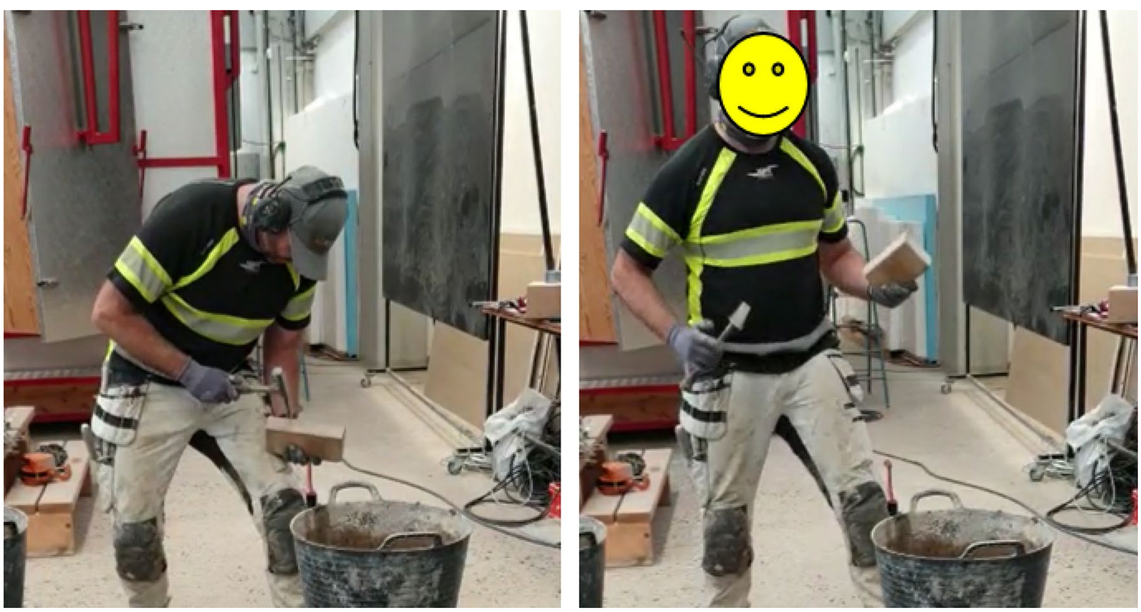

Fig. 4 Generate normal, half sized bricks

bricks are in each of these uses laid in different pattern. Both related to visual and physical reasons. In practice also the length of a wall decides how different individual bricks must be cut and placed. Different thickness of vertical and horizontal joints is used and several different recipes for mortar are available.

2.2 Wall to build

For the brick experiments presented in this paper, we designed a curved masonry wall (Fig. 5). The base curve of each layer of bricks is a planar sinusoidal curve, where the amplitude decreases with the height of the layer above

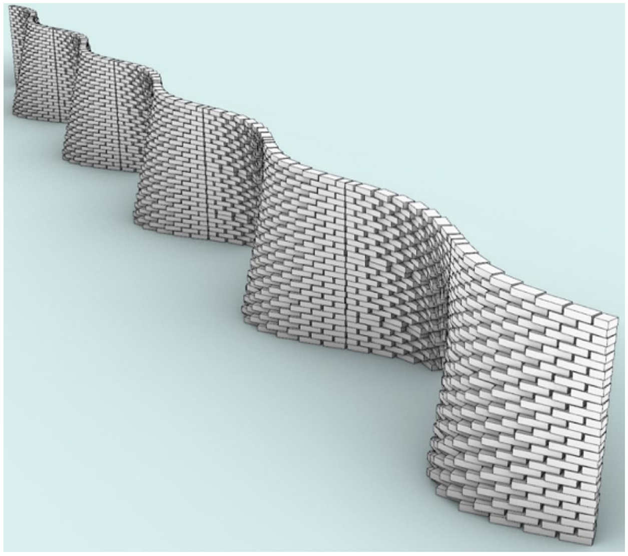

Fig. 5 Curved masonry wall

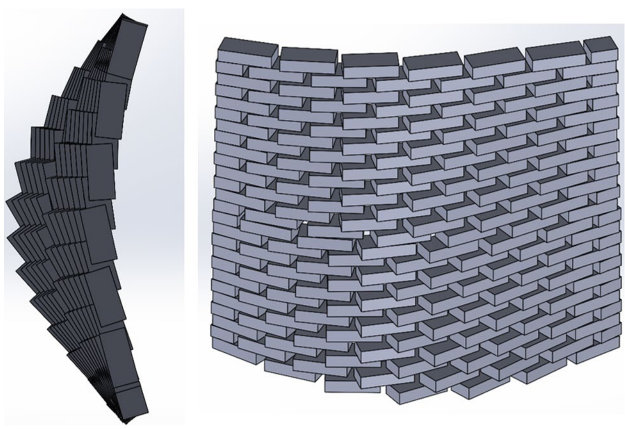

Fig. 6 One wall module used as reference for automated masonry process: top view (left); tilted front view (right)

ground. This shape offers the possibility to demonstrate the ability of changing brick placement.

Although we have analysed the manual processes for building a straight wall, we have decided to build a curved wall in our experiments. In general, curved walls are not built by practitioners. Hence, we try to extrapolate the knowledge from the manual straight wall to handle the design freedom of the curved wall. Mismatches, such as area coverage for mortar are interesting challenges, which need to be discovered.

While having a robot being able to directly interpret the wall's design, we can precisely control the exact position and orientation of individual bricks with our robotic masonry system, which is, manually performed, very challenging. The bricks to set are individually rotated out of the tangent direction of the base curves. This individual rotation is proportional to the curvature of the base curve at the location of the current brick, see Fig. 6. Thereby we create a wall with differently sized angles between side-by-side placed bricks, which causes differently sized vertical joints.

To enable robot systems for building walls, we need to extract more detailed information about the specific walls in comparison to the current state of the art. To handle the individual brick properties, like size, position, orientation, inaccuracies and different structured sides, the use of algorithmic tools is requested. Thereby, the possibility of manipulation of individual bricks in the design is opened. In our case, we first focused on position and orientation of each individual brick.

For creating the 3D model of our wall and for calculating the exact position and orientation of each brick, the algorithmic modelling extension Grasshopper to the 3D modelling software Rhinoceros 3D was used, cf. (https://www.rhino3d.com/). Algorithmic modelling tools are essential for robotic masonry since manual specification of the orientation and position of each brick would be impossible in larger projects, e.g., in a complete brick facade of a building.

Since the used design tool for building the wall shown in Fig. 6 only allows brick design for the moment, mortar extrusion pattern designs, which we are experimenting with, are not mature to include into the design tool, yet. Vertical mortar application is also not implemented so far since we are awaiting development of 3D print technology at our test riggs to allow quick start and stops in the material flow.

The 3D model can be used for visualising the finished appearance of the wall, but more important, the algorithmic model also exports the orientation and position of each brick to the robotic system to construct the steering code for the brick-laying robot, which is further described in 4.2.

3 Parallel-kinematic machines

In contrast to a standard arm manipulator where the robot links are arranged in a serial chain from the base of the robot to the tool, parallel-kinematic manipulators typically consist of a robot structure where several parallel links are attached to a common tool plate. The so-called closed kinematic loops together lock degrees of freedom for the position and orientation of the tool. The PKM's fundamentally different design allows for important properties like e.g., less moving mass and significant higher stiffness which may offer important benefits compared to standard industrial manipulators with respect to acceleration, positioning accuracy, structural rigidity with respect to process forces and e.g., footprint/workspace and complementary broadens the applicability and use of robots (Boer et al. 1999; Neugebauer 2005). The PKM configuration used within the project is based on a gantry frame and a novel wrist construction. It will be explained and its benefits within construction robotics for masonry operations in comparison to serial kinematics, will be highlighted and further discussed in Sect. 3.1.

3.1 PKM for brick masonry

In the previous work “Parallel-kinematic construction robot for AEC industry” (Klöckner, et al. 2020) our work-in-progress to adapt a PKM structure to automate a selected masonry process was presented. In the meanwhile, we have set up the PKM in the laboratory and equipped it with necessary hardware and software items to perform experiments.

The PKM is an eight-link parallel-kinematic manipulator that provides 5-axes continuous motion. There are six links that in three pairs connect the three carriages on the 4 m linear guides with the so-called support platform that positions the base for the robot wrist mechanism. Each of these six links have a fixed length of 2 m. By controlling carts on the three linear guides, the robot can perform translatory movement with the support platforms keeping a very stiff orientation. To provide stiff and precise tool orientation in two directions (tilting the tool, while keeping the third orientation stiff), two telescopic links are mounted between the upper and lower carts respectively. Together with a cardanic joint between the support platform and the tool platform, this results in controlled rotational motions around *x*- and *y*-axis. This type of machine provides a large singularity free workspace, high rigidity and precision, as also described in Cognibotics AB (2021). For PKM including its workspace see Fig. 7.

To fit with laboratory conditions the PKM is presently mounted on a horizontal support structure. Though it is also possible to mount it in a setup for working from top for example. Figure 8 shows the PKM connected to a support structure in a brick masonry process. The robot consists of the arm system and the rails. The column/support structure is needed to ensure enough stiffness and absolute accuracy for the application. In the built robot the support structure is dimensioned also for high accuracy machining applications by what the structure can take forces up to 3 kN. For less demanding applications, such as brick laying or raking (with low accuracy demands), the support may be less. We are investigating creation of a scaled down version suitable for placing on existing construction machinery.

To adapt the PKM for the described masonry process, we designed a tool (Fig. 9) containing two motors allowing rotation around *z*- and *y*-axis.

Moreover, the brick masonry tool consists of adapter plates and motors that transmit the movement generated by the motors into rotary tool motions via cross-roller bearings. The use of an L-shaped part allows the tool to point down in zero configuration. Furthermore, we decided to use a vacuum gripper consisting of three vacuum cups with 55 mm diameter each, equipped with filters inside to handle the dusty bricks and provided with foam to be able to create vacuum for gripping the rough brick surface. Flow regulation and control of vacuum gripper is realized with Avac injector MFE-300H-AS-1. With a connected 10 m long and 8 mm diameter air hose and 6 bar pressure, we achieved 60% flow. For easy and fast tool changing option RSP TC60-8 tool changer and RSP TA60-8 tool changing adapter are included in rotational *y*-axis.

For the mortar application process, we equipped the tool with an extruder mounted on the L-shaped part mentioned before and connected the extruder to a circular nozzle at its

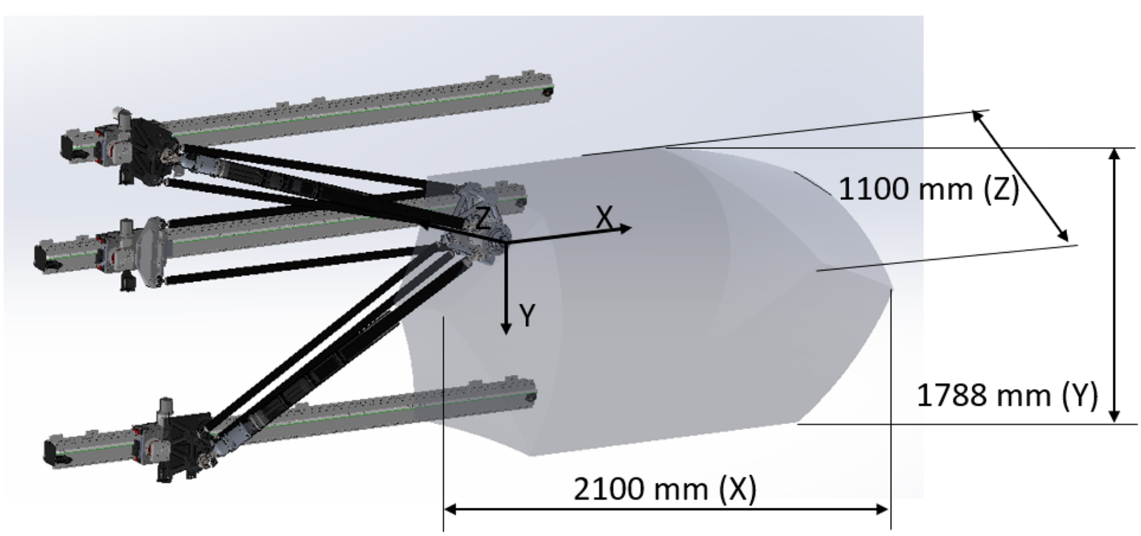

Fig. 7 Workspace PKM

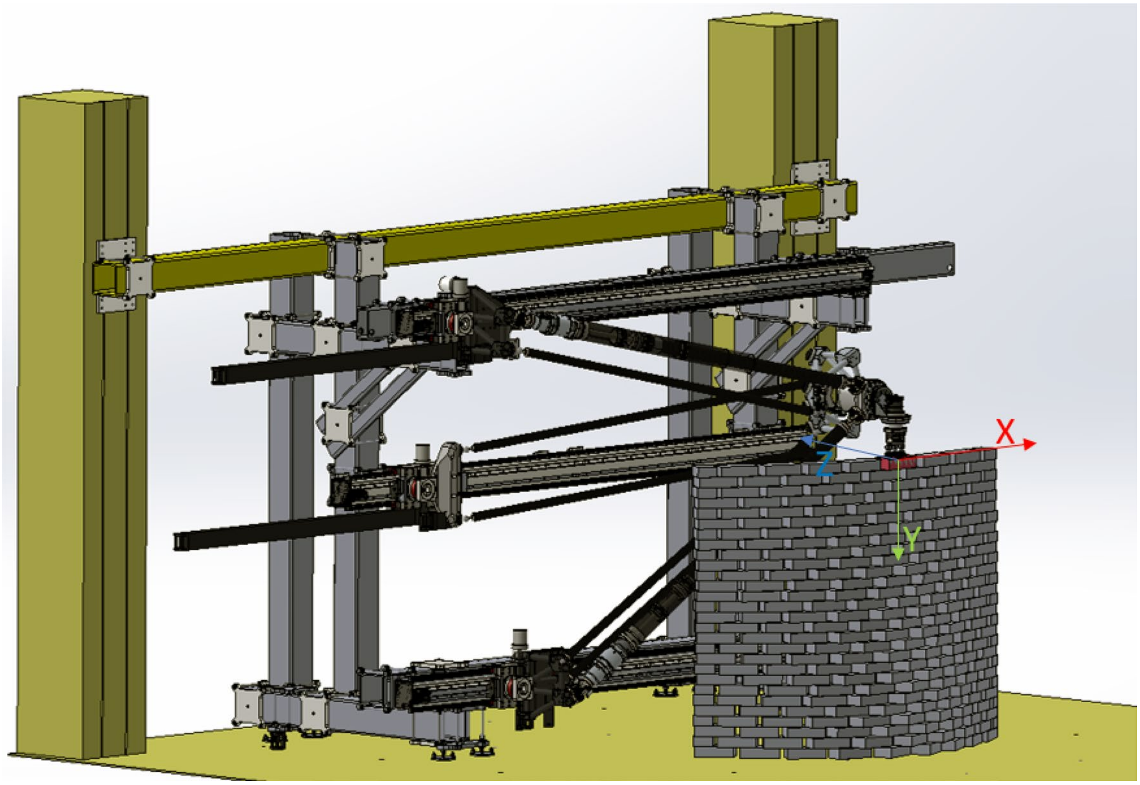

Fig. 8 PKM mounted on support structure in brick masonry process configuration

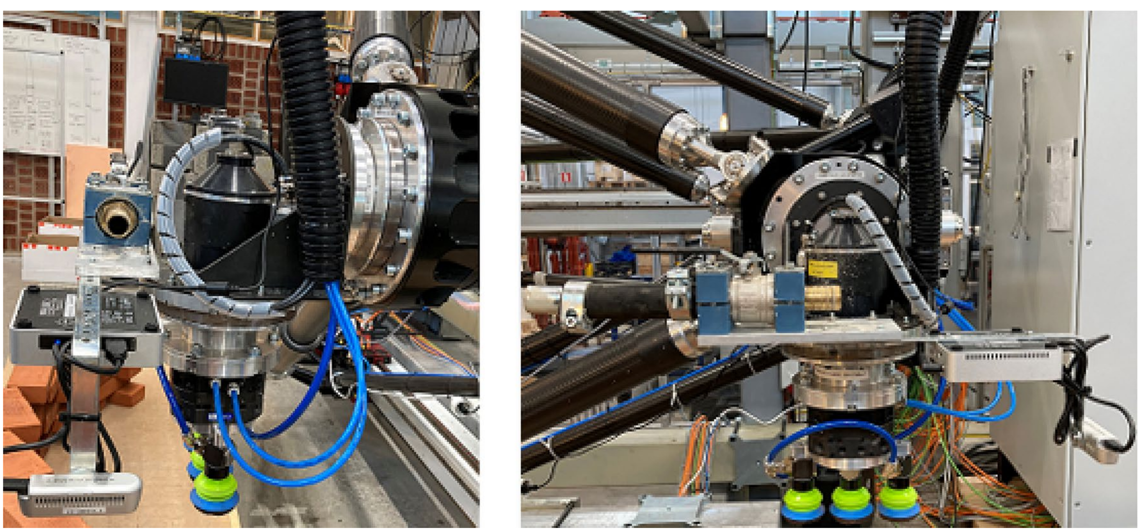

Fig. 9 Tool side view (left); front view (right)

end (Fig. 11 left). On the other end a connection for a hose is prepared which connects the mortar pump with the extruder.

To merge the so far described parallel kinematic machine and its components to adapt the parallel kinematic machine for construction robotic processes, Fig. 10 contains the hardware description. As seen in Fig. 10 the parallel kinematic manipulator is built in a laboratory environment and attached to a support structure. The PKM itself is controlled by a controller, which can be accessed by a connected computer as well as by a connected teach pendant. The applied control system is Beckhoff using TwinCat CNC. Tools for manipulation are connected to the robots end effector and contain one

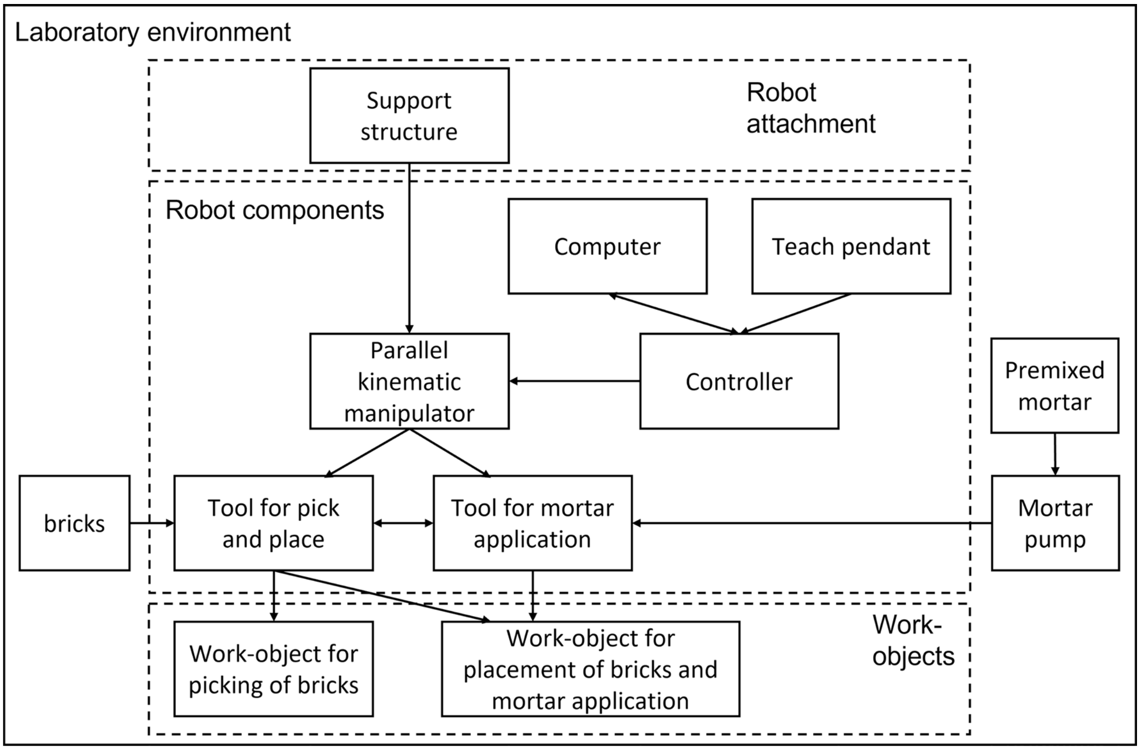

Fig. 10 Hardware description

tool for brick manipulation and one tool for mortar application. The work-objects which are used for manipulation performance are a work-object for picking of bricks and a work-object for placing of bricks and for mortar application. Objects needed for this manipulation are bricks and mortar. The mortar is put into the system as premixed mortar via a mortar pump connected to the mortar application tool.

In comparison to serial kinematics the parallel-kinematic machine foresees the work envelope, which is needed to build e.g., walls or to perform work on facades. Especially the fact, that the PKM is small in depth and long and easily extendible in one direction supports the use in the construction industry. Also, a simpler integration in existing construction equipment like robot carriers is supported by the weight distribution in the robot structure, i.e., low weight in moving parts as the arm system. Furthermore, its acceptable stiffness and accuracy properties to lower weight than serial robots allow for future integration on the construction site.

4 Experiments

For performing experiments with the developed parallel-kinematic manipulator, we built the experimental setup described in 4.1, generated the brick data needed for the parallel-kinematic manipulators programming and focused on the challenges to solve (Sect. 4.3). Furthermore, we performed experiments described in 4.4 to evaluate our proposed solution. Moreover, we list and discuss our results (Sect. 4.5), including successful realization as well as obstacles which had been occurred and possible solution options, which offer the base for conclusion and future work (Sect. 6) including Technology Readiness Level enhancement of the parallel-kinematic manipulator.

4.1 Experimental setup

Our experimental setup (see Fig. 11) located in the Swedish National Center for Construction Robotics (http://www.lth.se/digitalth/byggrobotik/) contains the PKM equipped with the following peripherals: Described vacuum gripper tool to handle bricks, a palette with bricks placed on stacks for picking application, a double sized palette equipped with a flake board for placing application, a controller, a workstation, acrylic glass walls for safety during robot execution, process peripherals connected to tool for mortar application, computer and Intel RealSense Depth camera for vision integration.

4.2 Wall data generation & transformation

For creating the steering code for the bricklaying PKM, data on each stone is exported directly from the algorithmic 3D model of the wall (2.2). In this project, this data is exported

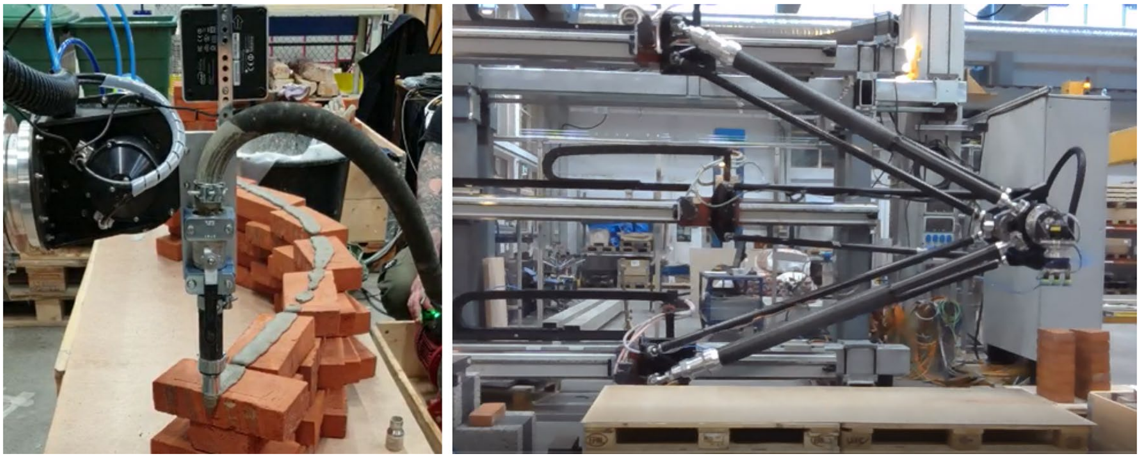

Fig. 11 Experimental setup: mortar glue configuration (left); pick and place configuration (right)

in the form of an automatically created Microsoft Excel spreadsheet file. Apart from the orientation and position of each brick, this file contains a column specifying the layer, and consecutive number on this layer from left to right, of the current brick. It also specifies if the current brick is a full-sized or half-sized brick. Half-sized bricks are used in the current design for having straight vertical ends of each module of the wall.

To feed the parallel-kinematic machine, which is programmed in G-code based on the data exported as spreadsheet file, a semi-automatic tool chain is used to transform from wall description to executable G-code.

4.3 Challenges

Challenges we are focusing on within our experimental performance contain implementation of a stable process for brick handling and mortar application by building the wall described in 2.2. The processes sub-challenges can be divided into: Pick bricks, move bricks, place bricks and apply mortar.

Though we focus in our application on one specific brick type, bricks are having, as experienced, deviations up to + / − 2.5 mm in width and height, while having a dusty and rough surface. Our gripper decision is based on the fact, that it would be most convenient to pick directly from a palette. On the palette the bricks are placed with no space in between each other and their upper or lower side points outwards the palette. For this reason, we decided to design a tool containing a vacuum gripper to be able to easy separate the bricks from the palette. For performing pick experiments with the chosen gripper in combination with the bricks to handle, we started to place bricks in stacks on a palette. To pick a brick with the vacuum gripper we need to be close enough to the brick to get it connected to the gripper. In case we drive too close the very sensible foam (grippability in this solution depends on the foam being able to create enough suction force) placed at the end of the vacuum cups releases its connection to the cup which impairs the flow we need to create the vacuum, by what we are not able to create enough vacuum to grip the brick. In addition, to offer a continuous good flow we have a filter implemented in the vacuum cups, which we clean by blowing of several times before we pick a brick and after we have placed a brick. A blocked filter also decreases air flow, which decreases the needed vacuum.

Moreover, the deviations of the bricks are causing bending in the stacks and displacement of bricks (see Fig. 12 (upper middle)). A calibration procedure matches the pick position in camera space with the corresponding position in robot space. Measurements during operation calculate the relative change in camera space to the calibrated position. The calculated relative change is then applied to the pick position in robot space.

Regarding cycle times and safety, we define speed and acceleration as fast as possible to not disconnect the brick from the gripper during acceleration and braking/emergency stop. We accelerate the bricks while connected to the robots' end-effector with 3.87 m/s^2 and moved them with a constant speed of 1 m/s.

In terms of placing, we had to handle possible unevenness of the lab floor. To handle this condition, we build a leveled plate on top of palettes and defined this palette as a work object to work on. For the described experiments we only considered local calibration. Additionally, we investigate placing strategies for dry stacking and for stacking with mortar between each layer as well as general design limits of bricklaying. Since all bricks have deviations, the deviations get bigger with an increasing number of layers during dry stacking performance. For this reason, we decided to place the bricks a few millimeters over the last applied layer and let it drop on top. For placing bricks on a mortar layer, we had to figure out, if the dead load of the

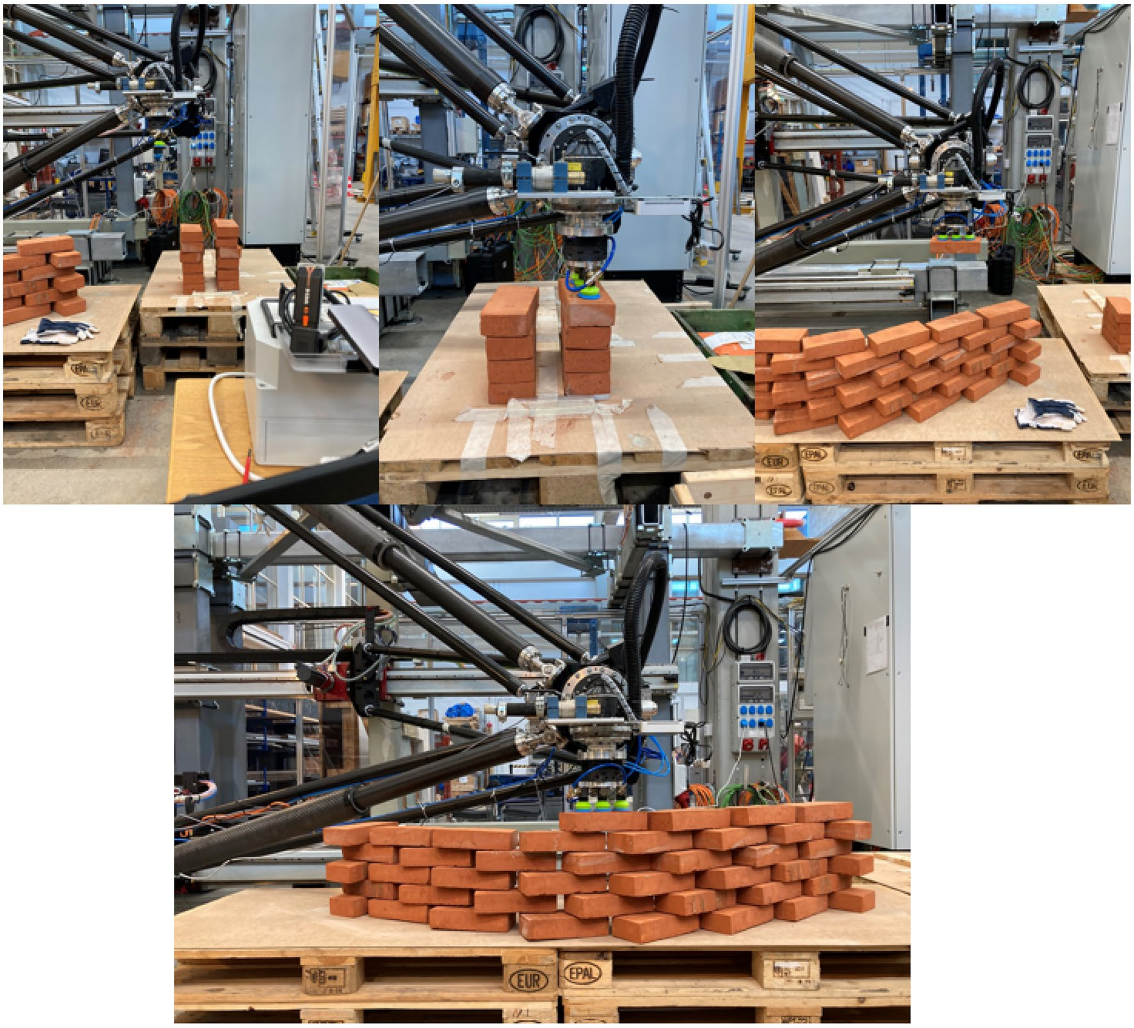

Fig. 12 Dry stacking process: taking picture for vision (upper left); pick brick (upper middle); move brick (upper right); place brick (down)

bricks is enough to get a good connection to the mortar or if we need to apply a defined pressure for placing the bricks on the mortar.

Due to process requirements and experiences from former experiments we decided to mix mortar glue according to the provided formula. By this we got the needed viscosity to get the mortar glue pumped through the hose as well as applied on the bricks. Furthermore, it is mandatory for a good process flow to apply the right amount of material with the right speed and the right consistency to achieve proper results. The aim is to apply pumpable mortar, which we are still investigating.

The robot system is currently calibrated using a laser tracker. Other methods for field calibration as provided by Cognibotics AB are in consideration.

Finally, design limits, including wall instability, will be caused by external factors like 10 mm joint height between brick layers, dry behavior of mortar and wall design itself as well as by internal process concerning masonry robotics hard- and software.

4.4 Experiment performance

Our experimental performance is divided into two main parts. First, we investigate dry stacking of the wall described in 2.2. Second, we focus on stacking the wall with different mortar application strategies. The process for dry stacking bricks with the adapted PKM for masonry processes includes driving to a defined position over the stacked bricks, taking a picture of the next brick to pick and calculate the displacement regarding the reference brick defined in the process preparations. Afterwards, the PKM drives to the pick position and picks a brick. Thereafter the brick is moved to the placing position and placed with the defined tilt around the y-axis (Fig. 12). The wall we build with this handling technology is shown in Fig. 13.

Fig. 13 Dry stacked wall

For stacking with mortar, we investigate different mortar application strategies with the objective to identify a strategy e.g. without spill and without exposed mortar glue. Therefor we first focus on mortar application on top of a built layer by generating two paths, see Fig. 14. Path A goes through the start point of the first stone, the midpoints of all stones and the endpoint of the last stone with a constant speed. Path B goes through all start-, mid-, and endpoints of every stone contained in the layer and is speeded up over the joints.

Since we investigate Path A as the best, we use this as the base to apply another layer of bricks on top, which is shown in Fig. 15.

To conclude the experimental performance, all process steps are visualized in the state machine diagram in Fig. 16 at the example for wall building with mortar. The diagram starts with placing a layer of bricks and does not take an application of mortar below the first layer of bricks into account. Since the current robot is built in place, we need to investigate a down-scaled version to get it mobile. This will offer us the possibility to get it outdoors for field tests on the construction site.

4.5 Results

Results we achieved by performing experiments with regards to the identified challenges are also divided into pick bricks, move bricks, place bricks and apply mortar.

The tool decision including two more rotational axes offer us to handle the bricks in the orientations and positions we need. Furthermore, with the chosen vacuum technology turned it out that the dustiness of the stones caused trouble, because it gets sucked into the air hoses and could, in long

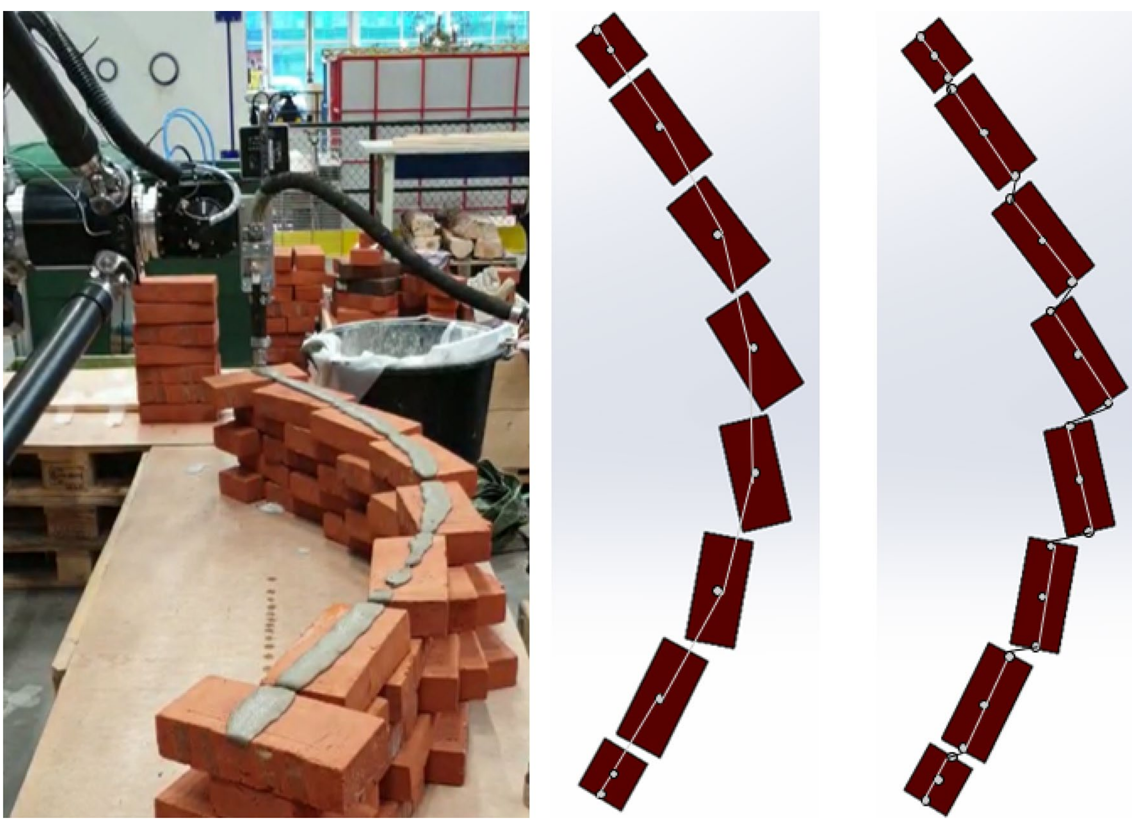

Fig. 14 Path A applied on layer of bricks (left); path A (middle); path B (right)

Fig. 15 Stones applied on mortar path A

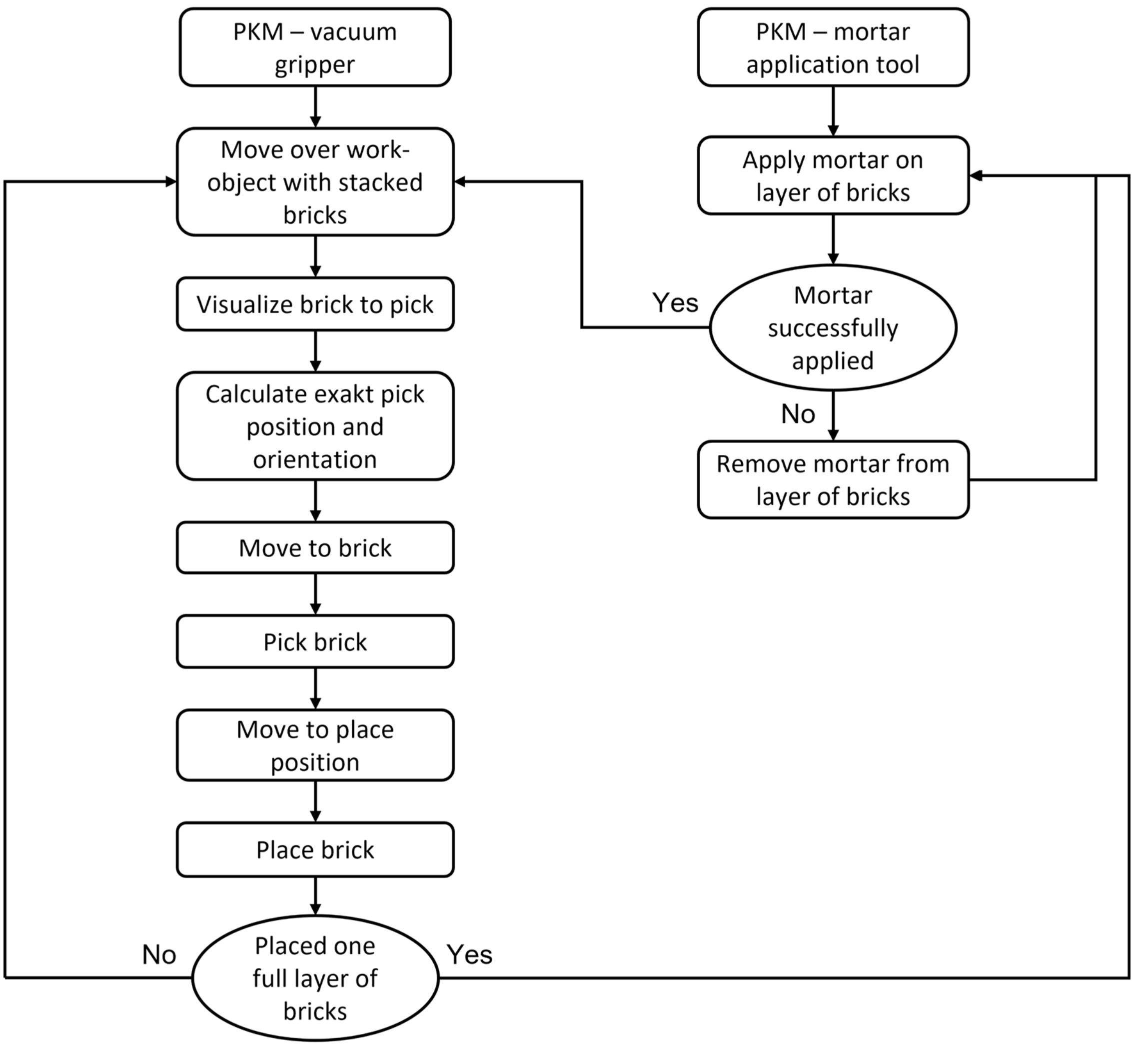

Fig. 16 State machine diagram for building wall with bricks and mortar

term, destroy the injector used for generating the vacuum. A proper solution could be to use another filter unit in front of the injector to offer a long-term use of this part. Furthermore, the vacuum cups turn out very sensible in case we drive too close to the brick while at the same time a good vacuum could just be created when we were close enough to the bricks. Implementing a force-torque sensor into the tool to identify the ideal distance between bricks and the vacuum gripper by control of pressure between these two objects would produce relief. Furthermore, the foam attached to the vacuum cups is very sensible. Investigating a Schmalz FQE-xb-120 × 60 with foam will be of interest.

Like mentioned the bricks to handle have individualized sides. The identification of the different sides requires the use of cognitive sensory integration into the process. Considering that the bricks need to be placed in a defined orientation and position to offer the best wall impression, a stationary vision system in combination with a further manipulator could be integrated into the setup.

The accuracy for picking the red Danish bricks could be enhanced demonstrably by use of the implemented vision system. The high variety of existing brick types opens the need to enhance the existing vision system for a more flexible future application.

Moving the bricks with the needed acceleration and speed worked very well with our configuration. In dependency on how close human and robot will work together in a demonstrated cooperation an additional gripping solution could be used when the bricks are moved by the robot to avoid disconnection of the brick during movement, which means to avoid possible injuries by a flying stone to a human for example. Cycle times which we achieved within our setup for continuous brick handling are 145 bricks/hour, with time divided between pick (7 s/brick), place (4 s/brick) and travel between these positions (14 s/brick). Cycle times for manual brick handling are 300 bricks/hour, excluding breaks.

A possible force-torque sensor would also be very useful to enhance placing of the bricks. For dry stacking we would be able to handle the deviations in height by an appropriate control. For stacking bricks on a layer of mortar the force-torque sensor could help to push the brick with a predefined force into the mortar up to a predefined position and orientation, which adapts the stressed chord from the manual equivalent.

The application of mortar has different constraints. For applying mortar on a layer of bricks with a continuous flow and a constant dispersion we need, besides a specific material consistency, also a defined distance of 2–4 [mm] between the nozzle exit and the bricks. For path adjustment in height visual depth cognition could be used.

For keeping the needed mortar consistency during experiments, we blended it with a hand blender, in a barrel connected to the pump, frequently. With regards to automation, a solution with continuous blended mortar in a mortar blender and an additional mortar supply mechanism at the end effector in combination with an on purpose-built nozzle could enhance the process quality. Since a lesson learned is that the mortar material needs to be adapted to the robotic process, we are now starting up collaboration with concrete suppliers partly based on our experiences from this work. Furthermore, we are investigating 3D print strategies for approvable mortar distribution patterns in the design space. However, this effort is still on low technical readiness level.

Our decision to apply mortar along path A (Fig. 14) is based on the fact, that this path overlaps almost with the layer of bricks it is applied on as well as with the layer of bricks which is applied on the mortar (see Fig. 15). Apply mortar along Path B ensures less overlapping with the layer of bricks it is applied on, as well as with the layer of bricks which is applied on the mortar path. For enhanced overlapping of mortar and bricks a mathematic model could be used to calculate the best performance mortar path.

Even if the curved wall design used in this project is more stable than a totally straight counterpart, improvements on the stability can, of course, be made. Stability would, for example, be greatly improved by making the wall two bricks deep and placing bricks in the wall which connects the two layers. This is a traditional way of creating a load-bearing masonry wall. The individual rotation of each brick is also introducing instabilities in the wall, both during construction and in the completed wall and while designing the wall we must be convinced that the forces applied on each brick will not push it out of place. It must also be checked that the down-facing side of each brick rests to at least 50% of its area on bricks in the layer below. This is essential for the adhesion of the current brick to the bricks below to guarantee stability.

Building time for the whole process regarding use on the construction site includes the following process steps: Transportation to the construction site, robot set-up, calibration, process performance, cleaning of mortar components and robot packing for resting time. Times we have determined for individual process steps in the laboratory environment are shown in Table 1. For time determination of the processes steps for field tests, we need to scale down the arm-system to meet the form-factor that fits existing construction equipment. Since the arm system is light weight, it is very suitable for down-scaling in future applications.

Since the speed and acceleration of the robot is determined by e.g., used motors, gears and the arm-system, a change of the robots' individual properties to better fit the application will also improve process performance results.

Furthermore, the camera we are using for the implemented vision is also connected to the robots end effector. Thereby, we need to drive over the palette to detect the next brick to pick. Execution time of the algorithm and

Table 1 Process times

Action	Time	Annotations
Transportation to construction site	No time estimation	Depends on distance between stored robot and construction site
Robot set-up	No time estimation, yet	Includes placement and opening of transportation box, so far the robot was set-up once in the laboratory, but set-up time for real construction site will differ
Calibration	No time estimation, yet	
Process performance	Brick handling: 145bricks/hour Mortar application: 1575bricks/hour	Continuous brick handling; Continuous mortar application
Cleaning of mortar components	30 min	
Robot packing for resting time	No time estimation, yet	Packing solution for transportation and process performance is under development

communication between the controller and the used robot for vision integration are calculated within the pick time. By setting-up a stationary camera system over the palette, the algorithm execution could be done before the robot reaches the palette with the brick to pick, which would shorten the cycle time for picking around 3 s.

In this setup the robot absolute accuracy is 0.4 mm. For the application the camera setup adds a variation depending on the projected pixel size. Furthermore, the handling tool itself, which has some lenience in the vacuum cups introduces inaccuracies. Regarding the influence of the inaccuracies of the handling system regarding construction robotics applications like wall building, which we investigated in this context, built walls need to pass visual inspections. A standard which is used for approval of built walls is DIN 18202 - Tolerances in building construction - buildings (DIN 18202). This standard relates amongst others to flatness tolerances of the surfaces of walls.

Wall assembly and transportation of prefabricated walls are issues, which are currently performed manually. Improvements remain, at this stage, open issues.

5 Reflection on process transformation in construction robotics

As already mentioned in the introduction the transformation from manual performed processes into automated process equivalents as well as the extraction of silent knowledge out of manual processes to transform it into robot motions for particular applications are still unsolved challenges, although they are invented for years. 2005 (Beumelburg 2005) Katharina Beumelburg has started up to divide manual performed assembly processes into process parts to decide based on a self-developed decision tool, which of these processes are pleasant for automation and which are pleasant for manual performance. This approach is already very promising, but still lacks decision opportunities on how to transform the for automation identified processes into automation equivalents. (Deuse et al. 2014) in addition to Beumelburg (2005) developed a decision system. This system helps to identify automation relevant manual processes and includes suggestions for the configuration of the robotic system. The robotic systems configuration includes e.g., suggestions for robot dimension, kind of tool and mobile or stationary system. Moreover, a planning system was developed which created motion plans for the specific viewed process with the configured robotic system. Additionally, (Klöckner et al. 2015) investigated the influence of different combinations of working tasks on the decision how to automate the whole process and which subtasks will be automated and which will continuously performed manually.

Anyhow, these are solutions for indoor applications, which for our case would need to be extended to be applicable for a very undefined, unstructured and fast changing environment with less repetitive tasks—the construction site. Since there is no existing usable approach so far for the robot automation for construction processes, we took our decisions for our first processes as described in the next paragraphs.

As described in Sect. 2 and 3 the manual performed labour to build a wall included:

- Preparation environment: set up frame, set up chord for levelling of layers.
- Preparation material: mix mortar, set tools in place, set bricks in place.
- Performance for building wall: Apply mortar, pick bricks, move bricks, place bricks.
- Postprocessing: Joint finishing, plastering, cleaning.
- Human: Process knowledge, wears protection cloth and safety glasses and gloves, can clean himself when needed.

First, I want to describe how we adapted the listed manual process steps for our automated lab experiments and later on I will describe what needs to be changed for outdoor use.

To prepare the environment, we have set up a special surface to build on. To adapt the frame as well as a specific chord for levelling, the combination of the high precision parallel kinematic with integrated sensory for equal level assurance could be used. In terms of material preparation, we kept the manual labour for mixing the mortar. Here we need to fill mortar powder and water into a bucket and mix it with a mixer. Filling materials into tanks/containers/buckets is still very common to be manual performed in industry. In comparison to just put the needed tools readily to hand, we had to mount the needed tools close to our robot's head. Here we mounted a gripper to be able to pick, place and move the brick, as well as a nozzle, connected to a hose, connected to a mortar pump, connected to our premixed mortar bucket. To set the bricks in place, the human is able to grab them direct from a palette on which they are delivered. To be able to do the same, we performed our experiments with a vacuum gripper. Unfortunately, we experienced that the vacuum technology has a very high wastage when we apply it for dusty object handling. Therefor it is not reliable in long term. Thus, we decided to unpack the bricks by hand into stacks to get the bricks separated from each other, by what we are also able to pick with a parallel gripper finger tool, which is not very applicable for direct pick from a palette. For building the wall, which has been our focus, the mortar application and the placing brick process differs especially. In manual labour, we apply mortar for each individual brick, place a brick, apply mortar for the next brick, place another brick and so on. In our automation equivalent, we apply mortar on a full layer of bricks with a different dispersion in comparison to the manual labour and set another layer of bricks on top. This is an excellent example, because it illustrates that we had to change the process order to set the automation equivalent up in a wise way.

Regarding the post-processing, we did not implement joint finishing so far, because it would need another tool and more sensory integration. We tried out plastering. For this process we also had to change the process order. In manual labour you apply plaster material on the wall change tools and disperse the material on the wall. In the automation equivalent, we continuously apply smaller amounts of material and disperse them directly on the wall. The cleaning itself, we did manually. The robot in comparison to the human does not have any process knowledge, so we need to feed him by integrating sensory to give him eyes and haptic feelings for example and by programming him to tell where he needs to move and how he needs to move, with which speed and acceleration and when he needs to grab something and when he needs to release an object.

If we use the robot indoors, we do not need to protect the robot from environmental influences, but we have to protect the humans in the surrounding from the robot. The safety integration becomes an important topic. Especially when we transform our application area outdoors, we need of course protect the robot from the environmental influences, like e.g., rain, snow, temperature and dust, but we also need to implement safety parts and strategies to offer a safe human machine interaction/side-by-side operation on the construction site. Due to the fact, that construction sites are still the most dangerous workplaces, we want to make it safer using robotic components and not worse.

6 Conclusion & future work

Within this paper we have shown our recent work-in-progress in terms of testing, for the brick masonry process adapted parallel-kinematic machine, to Technology Readiness Level 3–4. Since we have validated our predefined assumptions through dry stacking of bricks as well as through stacking bricks with mortar our investigations are highlighting the potential of parallel-kinematic manipulator's use in construction robotics. This lays the foundation for former explorations including enhancement of future process performance and parallel-kinematic behaviour.

Future work contains implementation of improvement opportunities into the current setup, which includes entire process improvements to be able to perform construction robotics processes directly on the construction site. This contains particular content, discussed in 4.5 and will mainly focus on further sensory integration for brick handling (pick, place, move) as well as enhancements of mortar application tool-design and mortar application strategies. Furthermore, we will focus on digital chain improvement to generate executable G-code directly out of the used CAD environment. Moreover, we will implement safety and interaction issues for enabling the PKM to be used for prefabrication processes close to construction site with the aim to bring the PKM up to a higher Technology Readiness Level. Our idea to use the PKM on the construction site itself, is to mount the arm system on site onto specific, application-oriented support structures.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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