Bettan – Industrial robot and application for Finja Exakt build system

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Abstract – This paper reports on efforts to create a robotized construction build system, based on the Finja Exakt manual build system. The equipment used is a generic off-the-shelf industrial arm robot integrated with a spindle crane carrier for mobility. The approach offers technical, safety and usability challenges as well as integration and business challenges for placing a generic industrial robot onsite as part of an automation solution. The question we address is if a robotized build system is a viable niche for industrial robotics in construction. In this paper the question is partially answered by reporting on an industrial robot partially adopted for work on a construction site with evaluation of individual processes in a build system.

Keywords – construction robotics, build system automation, Finja Exakt build system

1 Introduction

The electric industrial robot arm is the main work horse of the robotized part of manufacturing industry. It is typically used as automation solution in several niche applications such as palletizing, welding, assembly, conveyor picking and cutting as well as bin picking and 3D print. The robot is optimized for high performance in repeatable accuracy and cycle time. It is considered part of a "machine" and is therefore according to regulations certifiable only in its application [1]. Typically, safety aspects demand protection from human access during operation. Therefore, automation solutions utilizing robots are usually organized in work cells with protection barriers and structured input/output material handling. Recent years have seen the development of cobots (collaborative robots) to somewhat loosen safety restrictions, but such robots are typically severely limited in capacity.

Figure 1. The mobile robot system Bettan (top) and the house type targeted by the robotized Finja Exakt build system (bottom) [11].

Placing an off-the-shelf robot arm onsite at the construction site poses challenges. Literature lists hampering factors such as high initial investment, risk for subcontractors, lack of interoperability, lack of tolerance management, immature technology, unproven effectiveness, lack of experts [2,3,4]. But there are also concerns for low productivity of regular construction equipment [10]. There are basic challenges, i.e., withstanding conditions of a new environment,

Figure 2. Steps in the manual masonry process in the Finja Exakt block system. From left to right: a) First layer. b) Customization of blocks. c) Door openings. d) Mortar application. e) Reinforcement application. f) Customization for cabling. [12]

withstanding splashes and dirt from new materials used in the process, as well as transport logistics and usability onsite. Current industrial robots are built for environments in manufacturing which could be harsh, such as foundry, but it is still not possible to purchase a robot branded for construction environment. Available tools for setup and installation of robots are optimized to support batch production. Flexibility to quickly change task and/or re-localize a robot setup with minimal and non-expert human intervention is less supported. Regarding basic robot properties, an industrial robot is optimized for cycle time and requires a stable mounting surface for full performance utilization. At the same time the payload to weight ratio is low, to guarantee repeatable accuracy at high speeds and accelerations. That said, the industrial robot is a robust automation solution within its niche tasks.

The transfer and adaptation of an industrial robot automation solution from the manufacturing sector to the construction sector is examined in this paper. Early indications has shown that the typical tasks within a build system, as the one examined in this paper, maps well to existing robot niche tasks. Solutions for handling variation through workspace sensing is also becoming more common with the technology possibly being transferable to the construction site. Being able to build on available automation experience and re-use established roads to automation solutions with current off-the-shelf technology would benefit automation solutions for construction. It is an avenue worth visiting to gain experimental data on the feasibility of the approach. Related efforts are seen in [5,6].

There are basically two views for onsite material manipulation using industrial robot automation solutions. One is to build a specialized machine where the robot is integrated in the machine as part of the solution. The SAM100[1] bricklaying machine and the Hadrian[2] block laying machine are examples of this approach. The other approach is to view the construction task as an application for the industrial robot and provide application-specific packaged software, tooling and setup means for the robot on the construction site. It offers a bit more flexibility in the sense that the application is more tightly knit to a generic industrial robot and therefore might scale better with the possibility of switching applications. On the other hand, it does require to solve safety and certification of robots in applications on site. The robot presented here together with tooling and software explores creation of a construction robot and an application for a robotized Finja Exakt build system.

2 Finja Exakt build system

The Finja Exakt build system[3] consists of a family of insulated blocks. The family consists of three separate siblings with different width: 290, 350 and 400 mm, respectively. Typically, one width is selected and used. Within each sibling a few block variants exist, mainly varying in placement of insulation in order to handle different build situations such as corners. Blocks exist with two heights, slightly less than 200 and 100 mm, with a praxis of adjusting wall heights using one layer of half height blocks and the rest with full height. The length is slightly less than 600 mm to allow for a 600 mm placement zone in the wall. From the standard length there is a need to cut and customize blocks into specific variants. This typically happens at windows, doors and corners. The weight of a block is between 15 to 20 kg depending on variant. The system is named Exakt (Swedish for high accuracy) because the blocks are manufactured with high tolerance in measurements. This allows blocks to be assembled into walls with small accumulation of errors. There is therefore little to no need to compensate for errors so the mortar layer between blocks can be very thin. In the Exakt system blocks are used with a mortar interlayer spacing of 3 mm. This is also the motivation for the selection of this build system

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[1] https://www.construction-robotics.com/

[2] https://www.fbr.com.au/

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

for robotization as low variation in the main work object makes the system better suited for robot handling. The weight of the block and the size of the wall also fits medium-sized industrial robots well. The selection of robot for this build system, the ABB IRB 4600, handles double the payload of one block leaving around 20 kg for tooling and dressing. The robot reach of 2.5 meters matches well to the height requirement of a wall of 2.9 meters. The weight around 550 kg fits the selection of spindle crane as carrier well with the combined weight of carrier and the robot doable for a concrete slab.

2.1 Robot tasks

A mapping of robot tasks to Finja Exakt build tasks reveals standard robot operations to be performed; pick and place, depalletization, machine tending and 3D print of mortar. However, calibration procedures, normally part of an initial setup, here need to be part of the ongoing process. Because of non-rigidity in the robot structure the robot base system is non-Euclidean (curved) and not easily globally aligned with a house system. Also, the work object (house) is much larger than the robot workspace requiring a smaller robot to move around to reach the entire house with a need for recalibration to not lose position accuracy. These error sources together with other possible uncertainties (one example is placement of the robot on lose ground outside the slab) require the robot to maintain the robot base system or even local work frame relation to the house system as part of the process.

Manual operations in the Finja Exakt build system follow predefined steps, as illustrated in Figure 2 and specified in the Finja Exakt build instruction[4], used with blueprints. In short, the first layer of blocks is laid down with care for accurate placement of openings and care taken to achieve an even layer height. The application of mortar is performed by using a special tool (white box, Figure 2). Reinforcement is applied every few layers. Custom block sizes which are needed for corners and openings (windows and doors), are generated by on-site sawing of blocks. The first layer requires robot operations to be performed in a global coordinate system requiring millimeter-accurate external references and/or metrology systems. The second layer and up can be solved with local alignment techniques using surrounding blocks as references even though care must be taken to avoid error build-up. The current state of the robotized build system focuses on solving local alignment for utilization in the second layer and up. Besides calibration needs in-process, placement of blocks is a standard robot operation.

The Exakt blocks come factory packaged on pallets, requiring depalletization. A complication is that the blocks are oriented on the pallet with the block top surface vertical instead of horizontal. Also, the packaging is tight making it difficult to utilize mechanical gripping techniques. The isolation layer on the block makes vacuum a possible gripping technique but the need to grip from the side and coping with dirt makes long term robustness an open question. The current state of the build system is that it will depalletize using vacuum but assemble using mechanical gripper. In the longer run a change to Exakt block geometry to allow for mechanical gripping is to be proposed.

Manual distribution of mortar between layers is done using a distribution tool in the Finja Exakt build system, as seen in Figure 2. The mortar is pumpable, so the robot utilizes a 3D print technique to distribute mortar. A complication is the need to add reinforcement every few layers. The build system utilizes a nylon sheet being pressed into the mortar after mortar distribution before adding a layer of blocks on top. In the current state of the robotized build system automatic placement of reinforcement is not addressed.

Customization of blocks is the last task in the Finja Exakt build system. There are two basic cuts used. The straight cut is used to adjust the length of the block and is mostly used to adjust blocks to suit openings, doors and windows. The other cut is a rectangular cut-out for corners to optimize use of insulation. The needed block size is measured and cut to fit in-place for each individual placement, but a common cut is the half block to allow for an interleaved layering of blocks. For the robotized build system tending of an automatic saw is utilized. The robot is responsible for accurate placing of a block in the saw, and removal of block pieces after a cut. The cut is performed by the saw.

3 Further challenges

This section develops the discussion of challenges further. Besides basics of deploying an industrial off-the-shelf robot onsite as mentioned in the introduction and challenges in development of robot tasks for a new environment as discussed in section 2, we have also encountered and/or foreseen several other challenges:

- Safety, ergonomics and certification for onsite
- Usability, collaboration and sensing onsite
- Preparation onsite
- Impacts of mobility and reachability on execution of a build plan
- Material flow and tending in execution of a build

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[4] https://www.finja.se/produkter/block/isolerblock-exakt?id=16292060

plan
- Tooling
- Outdoor environment
- Level of autonomy
- Integration into digital tooling
- Business case

The list is by no means complete but a reflection of work-in-progress. There are ergonomic reasons for considering a robot solution. On a general level construction sites belong to the most dangerous workplaces, including injuries through unergonomic work, injuries through accidents and fatal accidents [7,8,9]. A study performed early on at a construction site using the Finja Exakt build system revealed several risks associated with heavy lifting, working on heights and sawing. The risks were not necessarily specific for the build system but nevertheless exists with the build system. To provide a safe work environment for human and robot on the construction site, safety concepts are required meeting the requirements of the machinery regulation [1] in combination with construction directives. In Bettan safety is currently managed by requiring an operator with a deadman switch, within enclosure or with requirement on (non-)presence of personnel. However, design of a non-monitored and CE-brandable safety solution is still an open question.

The same construction site revealed the challenge associated with moving equipment around the slab with obstructions such as placement of material and hoses sticking up from the slab. In Bettan physical repositioning is a manual operation using built-in tracks. There is currently no data on possible repositioning issues caused by obstructions. Repositioning without concern for obstruction is a quick operation.

3.1 Robotized build process

The traditional work scheme for a robot is to stay stationary, protected in a cell, and manipulate material flowing in and out of the cell. For part of a build system this might work well, such as customization of blocks through sawing in the Finja Exakt build system. For other tasks, needing manipulation of a work object much larger than the work volume of the industrial robot, there is need to extend the reach. In the Finja Exakt build system this occurs during placement of blocks and distribution of mortar for blocks.

Our selected approach is a semi-automatic system where an operator utilizes the robot equipment as a tool to perform tasks in the build process. To make the robot usable for construction site workers, the robot system need to be simple to use with little robot knowledge required.

Using industrial robot equipment require planning in where to place material and planning of a build route. The current concept is to plan the robot build process in digital tooling together with the house design and provide robot build process information with the blueprint that can be used in a preparation of a slab, for instance using bluelining.

Experimentally, we have selected as first step the adaptation of the manual building process for straight wall segments in one-story housing as illustrated in Figure 1. This includes adaptation of processes like placing strategies of blocks, strategies for mortar application and onsite sawing as well as transport logistics, tooling, cleaning and setup.

4 Preparations

4.1 Mobile robot for Finja Exakt build system

To adapt the Finja Exakt build processes for automation we configured an industrial arm robot on a mobile platform. The equipment was chosen to put a generic industrial robot onsite to evaluate challenges in doing that and challenges in application development for the selected build system. The equipment is not necessarily the optimum selection but rather the selection we opted for to perform experiments. The equipment is called Bettan (Figure 1). It consists of an ABB IRB 4600 foundry robot mounted on a Maeda spider crane (MC174CRM) where we dismounted the crane and attached the robot with a custom-made connection plate mounted on the rotational part of the crane. This offers the possibility to enlarge the robot's workspace, by rotating the adapter plate. The spindle legs suffice to keep the robot stable during operation if acceleration is constrained. There is no rollover risk with legs extended. The legs somewhat constraint reach since there is a limit on how close to a work object the robot can be placed. With a collapsed robot and retracted legs, the form factor is sufficiently small to pass through a door.

The tooling is developed specifically for the Exakt system and is multi-functional. It consists of a gripper for pick and place operations, currently a pneumatic Schunk gripper (SCHUNK PHL-W 40-100), equipped with fingers for Exakt blocks and vacuum cups for depalletization. This is combined with an extruder for mortar distribution as well as mounting positions for sensing, currently several RGBD cameras but also touch probe and force sensor for evaluation.

Since the form factor with robot and spindle crane is rather small there is little to no room for additional necessary equipment. This is currently solved by a trailing "umbilical cord" connecting the robot to external equipment being considered as extra "payloads" in the Bettan system. Each payload is usually mounted on an EU pallet or a movable trolley with the size of an EU

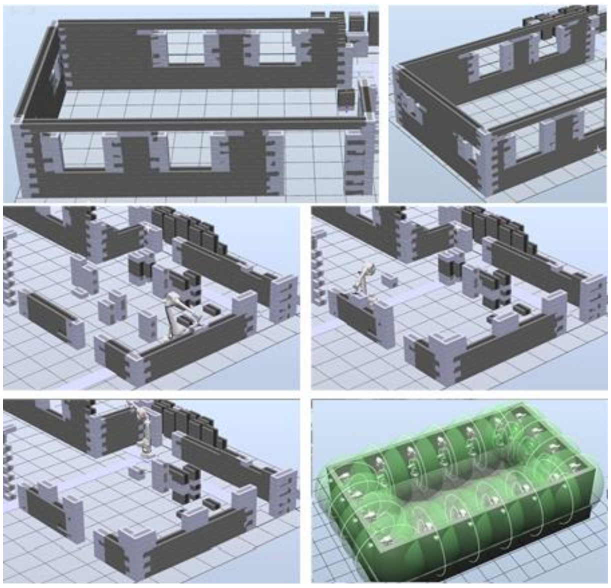

Figure 3. Digital preparation. From top to bottom: a) Parts of test house to build including straight walls, corners, openings for windows and doors (top). b) Disassembly producing stacks of blocks as material supply to a given assembly task of part of a test house (middle and bottom left). c) Calculating the amount of needed robot positions to disassemble/assemble the test house (bottom right).

pallet. The ABB compact robot controller (IRC5), the mortar pump equipment and air compressor are considered payloads. The idea is to form an "equipment island" that is moved seldom connected to a movable robot through the umbilical cord. In Bettan the equipment that is not weatherproofed is currently placed in the transport container. Construction tents are considered as well. The length of the cord is selected to allow for reach in the small houses that the system currently targets.

4.2 Digital preparation for process planning

It is common to develop offline simulations for robotized processes into CAD-like software tools to develop and validate the robot process. For a Finja Exakt robotized build process we also require a simulation. Apart from validation a simulation is also required as an end point to receive digital blueprints from external sources. The idea is to receive digital blueprints at block granularity level in nominal house coordinates, then add tolerances and letting the physical equipment solve tolerances through in-process sensing, also offering possibilities for logging sensor data for an as-built trace. This digital chain has been partly tested towards two external actors with different blueprint generation software, AChoice AB and Fojab. See Figure 3 for a generated one-story house blueprint imported into the ABB RobotStudio simulation software.

Another need is to prototype necessary planning methodology/algorithms regarding material and robot logistics to generate an execution plan and enrich a blueprint so this information can be utilized in prepping a slab for the actual physical execution.

The process planning addresses several aspects: Robot positioning, palette (material) positioning, order of blocks to pick and order of blocks to place. For the robot re-positioning we calculated the amount of needed robot positions to build the whole house with the requirement to move the robot as little as possible to avoid wasting time for robot movement. The positioning of palettes is based on the calculated robot positions and the reachability of the robot. The generated sequence order of blocks to pick and blocks to place is based on time as well as on reachability demands. Figure 3 illustrates robot positions that might need consideration when build a house with four walls based on the robot's workspace. A suggested starting methodology for planning is to "go backwards" and disassemble blocks of a test house and then rebuild. This to indicate a sequence of needed robot positions and required material supply at each position. Producing a timeline of build events with material supply in this manner is tested in a simulation, see Figure 1. A set of rules determine which blocks will be disassembled in which order and from which robot position. A sample rule is "If the block is a full block and lies completely in the area of the picked block from the layer above, pick the block". The method awaits practical evaluation onsite using the robot equipment to execute a planned build sequence. It is likely that bluelining or a metrology system will be needed to support the build.

5 Experiments

The robotized build system has in addition to extensive module tests in lab also been exposed to out-of-lab tests at two occasions so far. One occurring during summer and one during winter/spring weather conditions. The main focus of the first test was to test logistics and deployment onto a site with the second test focusing more on the application and gaining experience in repeating deployment.

5.1 Outdoor tests

Pre-outdoor testing at lab facilities included building small wall segments and trying out calibration techniques such as touch probing for fine localization. The build system requires between 2-5 mm accuracy per block for a wall to be approvable at inspection with individual block positioning errors not adding up to create overhangs. For a visually pleasing result it is also important that orientation errors are kept low to keep blocks in the wall aligned. Touch sensing has the advantage of being impervious to variations in lighting

Figure 4. Robotized Finja Exakt processes. a) Wall segment assembly (top left). b) Mortar application (right). c) Sawing (bottom left).

conditions. On the other hand, touch require multiple contacts to determine a coordinate system but is feasible if the number of necessary contacts is kept low. Unfortunately, the outcome of lab experiments showed that introduced errors because of non-rigidity in the robot and carrier platform made the robot absolute coordinate system sufficiently non-Euclidean for correspondence with a house coordinate system to be outside allowed tolerance limits. Consequently, frequent local measurements were necessary for local alignment.

Integration with external measurement equipment, i.e., trackers, could be used to uphold correspondence with a house system. Trackers are sensitive equipment and operate on a line-of-sight basis. There is a need to consider occlusion in a potentially cluttered work site. The lab facilities have access to trackers with limited work volume. Exploration of this option has until now been limited to lab experiments.

The first outdoor test was performed early September 2021 with fine weather. The experiment place was located some 20 km from the lab facilities with logistics solved using two trucks, as the lift capacity was not enough for a standard smaller truck with a 400 kg lift to solve transportation of the combined weight of carrier and robot. Payloads necessary to run the system was transported on the second truck while the robot with carrier was transported on the first truck. The system was powered from a portable construction diesel generator. The experiment consisted of packing (day before experiment), unpacking and deployment, performing part of the build system processes, packing and transportation back to lab facilities, performed during a six-hour experiment run. At the experiment site, the robot was positioned to work directly on the ground (the site did not have a slab yet). Despite one of the spindle legs being positioned on lose ground the robot behaved well during initial repeated pick and place tests performed at payload limit (40 kg tool + work object) with max speed but reduced acceleration profile (20 % of max). Lab experiments had determined the reduced acceleration profile threshold to be safe to avoid inducing potentially equipment-moving impulses. The process of constructing a wall segment was tested by picking blocks from stacks and placing to assemble the segment. A semi-manual calibration technique was employed in preparation of development of sensor-assisted local calibration techniques. The technique consisted of executing a nominal program as generated by our digital preparation tool chain, but with tolerance offsets to keep outside collision danger zones. At suitable positions in the program execution user interaction was asked for in terms of correcting the positioning of a held block towards the wall segment. Corrections were performed in a coordinate system suitable for human interaction with manual visual inspection of correctness. The manual correction process turned out to be rather effective with less than 30 secs needed for a correction. It does require entering the robot work area though. Still, the idea is to replace the manual correction process with an automated sensor-assisted process, with the manual process as a fallback option. As for the number of corrections needed for a program run of 4-5 layers of blocks two corrections were initially tried at the beginning of the program, at the start and end of the first layer. However, it turned out, that this was not enough and several more corrections were needed, either each layer or every second layer. Also, runs for gluing were performed.

The second outdoor test was executed during spring 2022 over longer period of time. The experiment site was located around 100 km from the lab facilities. Weather conditions varied from snowing to sunny with experiments being performed below roof or open sky. As lesson learned from the first test a container was rented for the equipment and was used for transport. This test featured several one-day deployment experiments to exercise setup and packaging of the equipment. It also saw a more full-ranged execution of build system processes, including wall segment assembly (Figure 4 top left), mortar application (Figure 4 right), and sawing (Figure 4 bottom left). Appropriate equipment was used with the robot for these tests, i.e., saw, pump, air, control cabinet and logistics for use of additional equipment was tested. Data was gathered to evaluate RGBD cameras as assistive sensing technology for local calibration in-process. Partial gathering of performance data was done.

5.2 Results

Table 1 summarizes the experiment results in terms of a scenario of building a small house similar to the one shown in Figure 1. The house consists of 1200 Exakt blocks (based on simulation in Figure 3) and around 20 % of those need adjustment through sawing. Measured values from experiments are marked with M. Estimated values are marked with P. Operations O1-2 involve repositioning of the robot. The number of repositioning's is estimated using the work volume of the robot and Exakt system regulations allowing stacking of only three layers of blocks in a short time. Operation O3 considers the robot at a fixed position, and not performed together with O1-2 in this scenario.

Table 2 shows estimated total time spent by operator (tending robot) and robot (automatic operation) for the operations shown in Table 1. Table 2 reflects our current target for Bettan, which is semi-autonomous operation using automatic calibration (current work-in-progress) and manual repositioning performed by operator (in the scenario every 9th minute). Automatic repositioning, we consider future work.

Table 1. Bettan time study for a small house scenario consisting of 1200 Exakt blocks. Headline Man = manual operation, Auto = automatic operation, Reps = repetitions. Operation O1 = place 1200 blocks at 100 robot positions, O2 = mortar application on 1200 blocks at 100 robot positions, O3 = sawing of 20 % of 1200 blocks. Time is measured in minutes and annotated with M = measured value from experiments, P = estimated value based on experience from experiments and/or simulation.

Operation	Man [min]	Auto [min]	Reps
O1a: Reposition robot	M 2	P 2	P 100
O1b: Recalibrate	P 5	P 0.5	P 100
O1c: Pick n place x 12		M 4	P 100
O2a: Recalibrate	P 5	P 0.5	P 100
O2b: Mortar startup		M 0.17	P 300
O2c: Mortar application		M 0.13	P 1200
O3a: Recalibrate	P 5	P 0.5	P 24
O3b: Replace material	P 5		P 24
O3c: Pick n place x 3		M 1	P 240
O3d: Sawing	M 0.17	M 0.17	P 240

Table 2. Interpretation of experiment data as total operator (manual tending of robot) and robot (automatic execution) time spent in a 1200 block house scenario based on data from Table 1. Assuming automatic calibration and manual repositioning. Note that time spent is based partially on estimated data. Time not directly related to robot operation, such as digital and onsite preparation for robot operation, is left out.

Use case	Tending [h]	Auto [h]
O1+O2	4	12
O3	2	5

6 Conclusion & Future work

The paper reports on efforts to automate a build system using an industrial robot made mobile as automation solution. The prototype is called Bettan. The build system selected is the Finja Exakt build system. Development of a Finja Exakt build system application for the robot has progressed so far that individual build system processes are fully or partially implemented and in the phase of being tested. The next step is further evaluation to approach the question of viability for industrial off-the-shelf robots as automation tools in build systems. The focus is not to build a fully optimised robot solution but to build a low cost robot that already in the short run is cost effective in a high cost country. The authors consider that such an application would have the largest impact on the use of robots in construction.

There is a need to allow spending of effort to develop higher level TRL complex prototype systems in risk sectors. In this case to try out a hypothesis of technology transfer from mature industry to immature (from an automation perspective). Higher TRL is necessary to reach and expose problems and issues only visible at higher TRLs, such as regulation, certification, business case, cost effectiveness, role among actors and in market, quantifiable societal and climate impact, besides technical issues. The Bettan demonstrator is currently developed throughout four research projects.

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