Mobile Robotic Brickwork

Automation of a Discrete Robotic Fabrication Process Using an Autonomous Mobile Robot

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Abstract. This paper describes the implementation of a discrete in situ construction process using a location-aware mobile robot. An undulating dry brick wall is semi-autonomously fabricated in a laboratory environment set up to mimic a construction site. On the basis of this experiment, the following generic functionalities of the mobile robot and its developed software for mobile in situ robotic construction are presented: 1) its localization capabilities using solely on-board sensor equipment and computing, 2) its capability to assemble building components accurately in space−including the ability to align the structure with existing components on site, and 3) the adaptability of computational models to dimensional tolerances as well as to process-related uncertainties during construction.

As such, this research advances additive non-standard fabrication technology and fosters new forms of flexible, adaptable and robust building strategies in the new emerging field of autonomous robotic in situ production−for the final assembly of building components directly on construction sites. While this paper highlights the challenges of the current state of research and experimentation, it also provides an outlook to the implications for future robotic construction and the new possibilities the proposed approaches open up: the high-accuracy fabrication of large-scale building structures outside of structured factory settings, which could radically expand the application space of automated building construction in architecture.

Keywords: in situ robotic construction, mobile robotic fabrication, adaptive fabrication, robot localization.

1   Introduction

Fig. 1. 'IF' – the 'In situ Fabricator', in motion from above.

The degree of automation in the construction industry is constantly rising, particularly in the area of pre-fabrication. On construction sites, however, the level of automation is rather low, and final assembly tasks of building components predominantly imply the use of manual labor (Gambao & Balaguer, 2002). This is a fundamental difference to other industries (e.g. the automotive industry), where the entire process from production of single parts to final assembly is often fully automated (Balaguer & Abderrahim, 2008). Therefore, robotic in situ fabrication – performed directly on the construction site – holds the potential to close the digital process chain between design and making (Helm, et al., 2014) and to leverage novel aesthetic and functional potentials in the field of non-standard architectural construction.

However, the inherent characteristics of construction sites substantially differ from those in factory environments, which make the implementation of fabrication tasks significantly more difficult. Building sites are generally considered unstructured[1] because they are gradually evolving and continuously changing shape during construction, floors are not necessarily flat and there is no guarantee for regular structures in the surroundings−as opposed to prevalent constant conditions in industrial production. Additionally, robots for pre-fabrication are commonly employed at an anchored position within a work cell and work pieces are brought to the stationary unit. Yet, to enable the fabrication of large scale building structures, which are exceeding the workspace of a fixed robot, the employment of robots on constructions sites requires them to be mobile.

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[1]   Within this paper, the term 'unstructured' is used to describe the environment of building sites, although, in most cases they can be defined as 'semi-structured', due to partially constrained and defined conditions (DeSouza & Avinash, 2002).

They need to be able to travel to the place of production and to move during construction, while still being able to localize themselves with respect to the working environment and fabricate structures accurately in space (Seward, 2002) (Feng, et al., 2014).
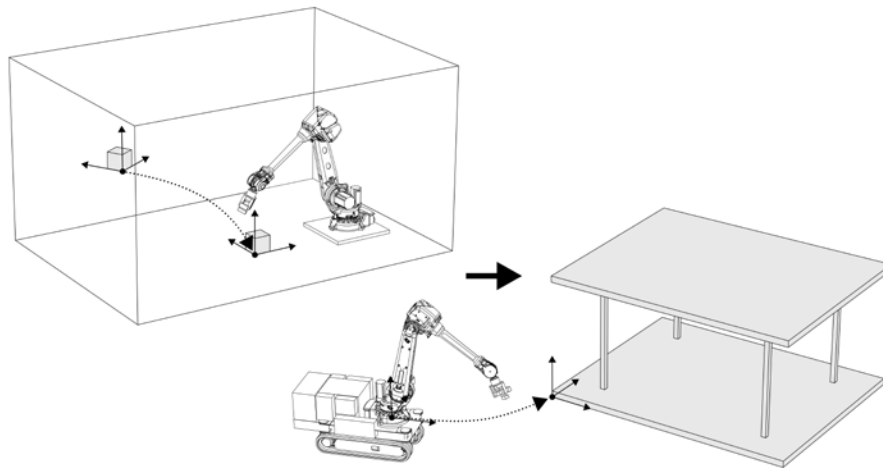

Fig. 2. Mobile in situ fabrication entails that instead of bringing the work piece to the fixed robotic work cell and referencing the work piece in relation to the robot (1) the robot travels to the worksite and needs to localize itself in relation to the working environment (2).

To take on these challenges, the two ETH Zurich groups Gramazio Kohler Research[2] and the Agile & Dexterous Robotics Lab[3] are developing an autonomous area-aware mobile robot, called the 'In situ Fabricator'(IF) . Following its predecessor 'dimRob' (Helm, et al., 2012), described in the next section, IF consists of an industrial robotic arm mounted on a base driven by hydraulic crawler tracks. It is intended as a generic mobile fabrication robot for the future employment on construction sites. This paper presents a first physical construction experiment using IF: the fabrication of an undulated dry-stacked brick wall, made up of discrete production steps, in a laboratory environment set up to mimic a construction site. The experiment serves to demonstrate the robot's generic functionalities and system architecture, as well as its integrated digital design and control software framework. In this context, objects of detailed investigation are a) the automated fitting of the geometric description of key features of building site components (e.g. floor, walls, pillars) to captured laser range measurements made by the robot, b) the precise robot localization using point cloud registration, and c) the adaptability of a parameterized brick wall's geometric description and its corresponding assembly sequences to process-related parameters during construction.

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2   Context

Concepts and exploratory setups to employ industrial robotic units for automated in situ fabrication tasks have been explored since the 1980s and 1990s, the most advanced of them being the mobile bricklaying robots ROCCO (Andres, et al., 1994) and BRONCO (Pritschow, et al., 1996). These early concepts however are characterized by heavy duty machinery and rigidly planned production routines. As a result, assembly procedures largely depend upon uniform, standardized building elements, standardized connections, strictly organized fabrication routines and well controlled environments. In the last decade however, robots have evolved through new developments in sensing, real-time computation and communication, within which inflexible top down organization principles are replaced by flexible and adaptive bottom-up approaches. These advancements allow also for their customization as advanced design and construction tools.

In 2010, the Gramazio Kohler Research group, together with the industrial partner Bachmann Engineering AG, developed and built IF's predecessor, the mobile platform dimRob (Helm, et al., 2012). It consisted of an ABB IRB 4600 industrial robot arm mounted on a tracked mobile base. Its hydraulic drive system was powered by a diesel engine and the system was steered manually using hydraulic levers. While dimRob already successfully demonstrated core concepts for in situ fabrication on the basis of a variety of experiments, its applicability was limited by a few key aspects. The original design of dimRob lacked the sensing required to allow the robot to build with high accuracy without being anchored to the ground using fold-out legs. This made it infeasible to build structures that would require the robot to move many times during construction. Also, dimRob had to be repositioned manually. This not only required substantial human intervention, but also placed a limit on the precision with which the robot could be repositioned. Finally, the robot arm was powered and controlled by a control box which was not integrated into the robotic system, which significantly limited the autonomous capabilities of the overall setup. This motivated a major revision to drastically extend its capabilities. The result is IF, the 'In Situ Fabricator', whose main features are described in the following sections.

3   IF Setup

3.1   In situ Fabricator System Architecture

IF is designed such that it can autonomously complete building tasks directly on a construction site. The level of autonomy intended for the robot is defined to contain all of the facilities required for precise manipulation of building materials. In this way, human interaction with the robot is narrowed down to the specification of building tasks through high-level planning environments and dedicated interfaces. In order to achieve this, the robot is designed to be self-contained, with all components needed for construction on-board: mainly sensing, control hardware, and computing systems. A dependence on excessive setup of the construction site for building is also avoided. For

this reason, the robot is designed such that it should not depend on external referencing systems (e.g. Nikon iGPS, Vicon, etc.).

3.2   Hardware Overview

IF features the same robot arm as its predecessor, but additionally it carries a complete, retro-fitted ABB IRC5 industrial controller. The whole system is electrically powered by lithium-ion batteries which enable it to operate for 3-4 hours without being plugged in. The robot's hydraulically driven tracks can still be controlled manually, but are predominantly operated in automatic mode where the tracks are steered precisely using an on-board control system. The drive system can achieve a maximum speed of 5 km/h on flat terrain at a total robot weight of 1.3 tons. IF's on board computer runs a real-time enabled version of Linux (Xenomai[4]), which allows for hard real-time data acquisition and processing, along with the robot operating system (ROS[5]). For the experiment described in this paper, IF was equipped with a Hokuyo UTM-30LX-EW laser range finder mounted on the arm's end-effector and an Xsens inertial measurement unit, attached to the robot's base frame. Additionally, the robot was equipped with a vacuum gripper to pick and place bricks, and a brick feeder on its back, which can carry 6 bricks at a time and has to be manually filled.

3.3   Computer Architecture and Communication

The high level planning of fabrication tasks, such as the sequencing of the robot's positions and brick laying procedures, and computing the arm and gripper commands, is implemented within the architectural planning tool Grasshopper Rhinoceros[6].
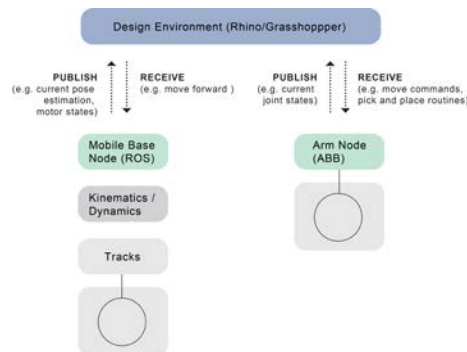

Fig. 3. Two separate processes control the robot's arm and base respectively. Coordination of the two is performed within Grasshopper Rhinoceros.

A custom TCP/IP implementation allows the online control of the robot's arm and base. Commands are sent through a Python interface within Grasshopper to the robot's ROS

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[4] https://xenomai.org/

[5] http://www.ros.org/

[6] http://www.grasshopper3d.com/

nodes for base movement, as well as to the ABB Robot Control Software for arm manipulation procedures. In return, all state and sensor data which is needed within the high level planning tool before and during construction is received within Grasshopper. Generally speaking, the robot's setup allows for feedback loops at multiple levels of the system. All time-sensitive tasks are executed by control loops running on the robot's low-level computer and the ABB controller, to control base and arm motion, respectively. The control of the overall building process, which is much less time-sensitive, is closed via the architectural planning tool.

4 Experiment

This section details an initial experiment performed with IF, in which a dry stacked double-leaf brick wall is constructed in between two pillars. The material system–consisting of discrete building elements and simple assembly logics–is specifically chosen in order to be able to solve basic problems of adaptive control strategies, construction sequencing and repositioning operations of IF, while still being able to subdivide the sequential building process into discrete production steps[7].

4.1 Adaptive Building Process

The building process begins once IF is moved to the construction site[8]. At this time, it takes a 3D scan of its surroundings, which serves as a reference scan for the robot's localization in space (see section 4.2).
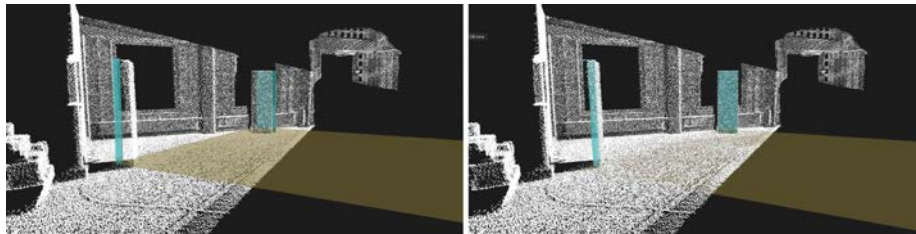

Fig. 4. Workspace geometry matching functionality of IF: the geometric description of existing structures within the building space (here: blue pillars and brown floor) is fit to a point cloud, captured by the robot when moved to the construction site. Notice how the brown plane, signifying the floor, initially lies above the scan points on the ground (left), but fits into the points after matching (right).

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[7] While a more elaborate hardware setup could have been employed to fix the bricks to each other and avoid the manual placement of bricks in the feeder on the robot, this was not done because these tasks did not fit the main goals of the experiment.

[8] Note that in this initial experiment, the robot was positioned manually via a remote controller. While the robot has all of the sensing and computing capabilities for autonomous navigation on-board, the development of the autonomous navigation capabilities required is left as future work.

Additionally, this scan is used to locate the true positions of key features of the working environment. These key features identify the interfaces to which the structure being built must attach (see Fig. 4). This information is then fed back to the architectural planning tool (Grasshopper), and is integrated as a parameter into the generation of the wall's geometric description (see Fig. 5). Since the true dimensions of the construction site generally deviate significantly from the ideal dimensions of building plans, and it is important to consider these inaccuracies before starting the construction.
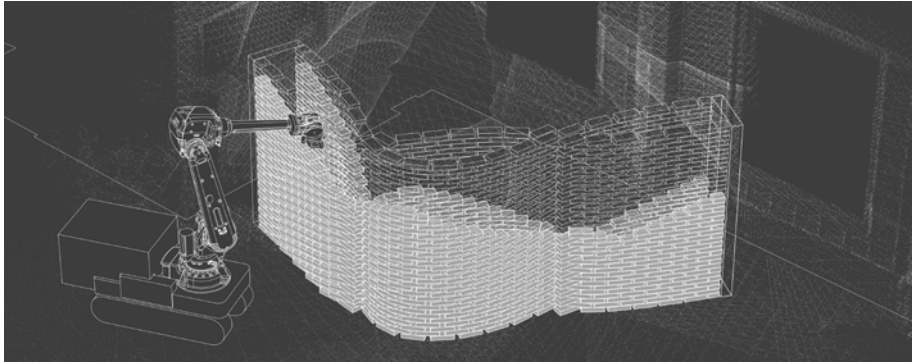

Fig. 5. A brick wall's geometric description is adjusted to the real-world sensor measurements of the robot. A mesh relaxation algorithm is used to align the individual building blocks' orientation and position with respect to the true location of the pillar, as well as to level the spacing between the single bricks.

As soon as the building environment is properly identified and the wall's precise geometry is defined, IF is moved to the first position required for building. When in the desired building position, it needs to localize itself (see section 4.2) and communicate its precise position to the high level planning tool within Grasshopper. Within the planning environment, the location information, along with the robot's reachability constraints, is used to determine a patch of bricks to be built (see Fig. 6). At this point, the robot can begin with fabrication.

As soon as IF has placed all bricks within its reach, it is moved to a new position. There it scans, localizes itself, and builds another patch of the structure. This process then continues iteratively until the structure is completed (see Fig. 7).
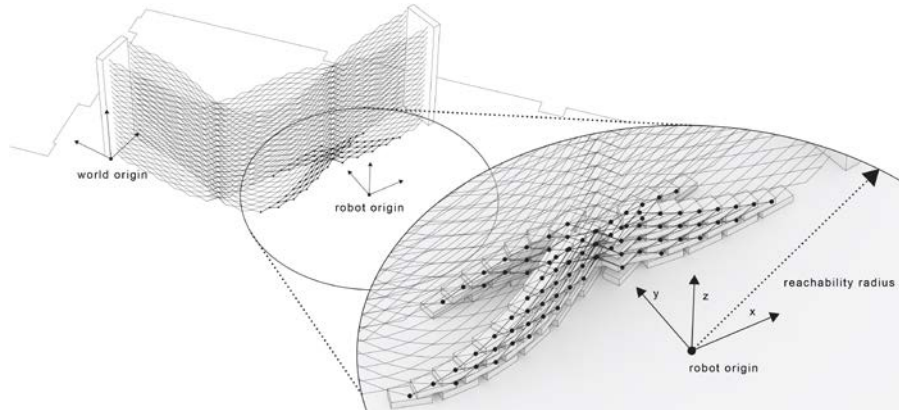
Fig. 6. The wall is stored as a graph, within which each brick is a node. Single patches of bricks to be assembled are generated from this graph, according to the location of the robot and the reachability constraints of the robot's arm. After the construction of each patch of bricks, the robot needs to change its position, localize itself and continue the construction from its new location.

Fig. 7. Simulation of one possible building sequence of the wall's construction: The double-leaf brick wall with the dimensions of 6.5m length and 2m height, consisting of 1600 bricks, is subdivided to be fabricated from 15 different positions of the mobile robot.

4.2   On-Board Pose Estimation

In order to build with high accuracy on the construction site, the robot needs to be aware of its position with respect to its work-piece. Because one goal of IF is to avoid dependence on external sensing systems, this means that the robot must be able to localize itself in its surroundings using on-board sensing and computing.

For this experiment, the primary sensor used for localization is a laser-range-finder, mounted on the end-effector of the robot's arm. By executing sweeping motions with the arm, 3D scans of the robot's environment are generated. Point cloud registration is then used to find the relative transformation from the current robot position to the reference robot position (see Fig. 8). Non-linear least squares optimization[9] is used to find the relative transformation which minimizes a measure of point cloud quality between the measurement and reference point clouds (Maddern , et al., 2012). This registration method requires no reference markers to be placed on the construction site a priori, makes no assumptions about the structure of the robot's surroundings, and is not severely impacted by objects which move within the site during building. For these reasons, this method should generalize to a wide variety of construction environments.
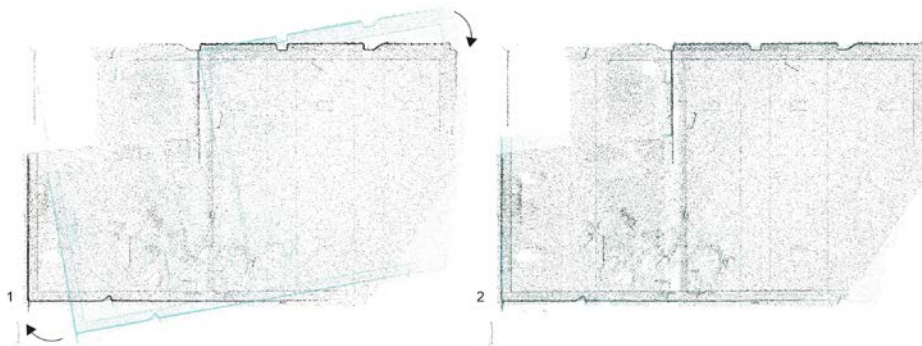

Fig. 8. Robot localization: Point clouds before (1) and after registration (2). Point cloud registration is used to find the relative transformation from the current robot position to the reference robot position.

Initial experiments showed that, with only static loading, the robot's base tilts up to 2° when the arm reaches far from the base. This can result in end-effector positioning errors of more than 70mm. To compensate for this base tilting, an inertial measurement unit is used to continuously measure the orientation of the base. This information is then used to adjust the target end-effector position while the arm is reaching to place a brick.

4.3   Experimental Results and Validation

The designed double-leaf brick wall was successfully constructed using the process described herein, requiring the robot to be repositioned 14 times. An average duration of 40 seconds for the picking and placing of a single brick was observed. While in the scope of the experiment it was not possible to directly measure the localization accuracy and the consistency between the final built structure and the initial design, the accuracy of the system was evaluated by measuring the position of placed bricks relative to previously placed neighboring bricks. These relative measurements were consistently within 3mm of the value expected from the CAD model. It was also observed that the bricks placed closest to the pillar opposite from where the robot started building were

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[9]   Optimization is performed using Google's Ceres Solver (Sameer Agarwal, 2015).

within 7mm of their expected position relative to that pillar. This indicated that global localization and brick placement errors did not accumulate over the course of the building process, since first, the pillar locations were only determined and considered before any bricks were placed, and second, every point cloud captured from a new location was always registered against the same initial reference scan. IF was therefore successful in building a structure which was aligned to existing features of the construction site using solely on-board sensing and computation. It is important to note that, in the experiment presented, a specific production sequence was not defined beforehand, but derived from the resulting locations of the robot during construction: While the human operator navigated the robot to an arbitrary location, the machine then identified and reacted to the resulting location and continued building with no further human interaction. While the automated navigation and optimized production sequencing of the robot is left for future development, the chosen strategy demonstrated a successful integration of human intervention and automated construction.

Fig. 9. Images taken from a time lapse video of the building process. The whole video is viewable at: https://youtu.be/loFSmJO3Hhk.

5 Conclusion and Future Challenges

5.1. Conclusion

The experiment presented in this paper demonstrates a significant step towards enabling the robotic construction of complex structures directly on the construction site with minimal human intervention. As mentioned in the previous sections, the continuous exchange of information between true measurements and the underlying computational model allows for the compensation of material and process related inaccuracies during fabrication (Sha, et al., 2009). With respect to the mobility of the machinery, production sequences can radically be redefined, which allow for the construction of continuous structures. These structures don't have to be discretized into separate building components due to constraints prevalent in pre-fabrication, but rather have to be redefined in accordance with the fabrication logics of the chosen material system, the mobile machinery and conditions on site. Eventually, this will demand novel mobile robotic building strategies, not only to realize complex design propositions directly on construction

sites, but also to enable design processes, whose formal language and constructive details comply with the fabrication logic of the respective machinery used.

Fig. 10. Experimental result: Double leaf dry stacked brick wall fabricated by the mobile robot. (Photographer: Michael Lyrenmann)

5.2. Future Work

Future research into in situ construction methodologies using IF will be focused on moving towards a more fully-integrated and continuous construction process, aiming at simultaneous arm and track maneuvers and continuous location-aware manipulation procedures. In this experiment, the robot base was driven and repositioned manually while the industrial robot arm was controlled from within Grasshopper. In a next step, these separate processes need to be unified in a whole-body control framework that allows to plan optimal, simultaneous base- and arm motions. This will then open up the possibility to address open questions like optimal building sequencing in terms of required energy or overall building time. Finally, formal influences in the design vocabulary through structural and process-related boundary conditions by using a mobile robot for fabrication need to be investigated—not only in the context of their functional, but also in their aesthetic capacities.

6   Acknowledgements

7   References

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