# Automated Localization of a Mobile Construction Robot with an External Measurement Device

**S. Ercan[a], S. Meier[b], F. Gramazio[a], and M. Kohler[a]**

[a] Department of Architecture, ETH Zurich, Switzerland
[b] Department of Mechanical and Process Engineering, ETH Zurich, Switzerland
E-mail: ercan@arch.ethz.ch, sanmeier@student.ethz.ch, gramazio@arch.ethz.ch, kohler@arch.ethz.ch

**Abstract –**

**The localization of a robot is a crucial part of any task that involves the mobile manipulation of objects. The precise repositioning of a mobile robot within the workspace is particularly important for on-site construction in situations where the operating area is much larger than the reach of the robot arm. This research presents a localization method utilizing a generic surveying and measurement device – a robotic total station.[1] The localization of the mobile robot in reference to the total station is investigated through the positioning of a reflector prism, mounted on the robot's end-effector, at different known locations in robot's coordinate frame. Through this localization method, the opportunity to remove the reliance on fixed reference points is tested in a large-scale outdoor experiment, which would alleviate the need for a full enclosure around the mobile robot to help constrain its pose.**

**Keywords –**

**On-site construction; Localization; External measurement systems**

## 1 Introduction

Robotic fabrication has traditionally been associated with high-tech industrial environments, where fixed positioning and constant conditions determine the role of the robot in the fabrication process. Unlike in facilities employing stationary robots, construction sites are spatially complex and unstructured, and mobile robots operating in such environments may be exposed to gradual change and unpredictable events [1]. One of the greatest challenges to the employment of robotic systems in such situations is maintaining their globally consistent localization (across a large building space), and assuring their perception of the immediate surroundings. In other words, a construction robot must "know" its own position if it is to localize itself and to manipulate its surroundings. In addition, every operation on a building site is unique in terms of the dimensions of the materials used and their range of tolerances. The methods adopted to facilitate the mobility of a construction robot on site should be sufficiently flexible to satisfy the various requirements of the building techniques and materials used. Accordingly, the two main problems can be identified as: (1) task-independent flexible global localization and positioning accuracy; and (2) task-specific local perception of the context.

This research addresses the first problem through a set of real-scale experiments in which the full potential of robot localization and positioning across a large building space is investigated using a generic surveying and measurement device of the type commonly used on construction sites. Rather than developing a task specific sensing device or technique, the goal is to explore viable methods of on-site robotic construction that do not require a full enclosure around the mobile fabrication unit. Such an In-Situ Fabricator (IF) would allow for flexibility in the production of building components larger than a workspace constrained by fixed references.

## 2 Background and Motivation

The mobile robot, the In-Situ Fabricator (IF), was developed within the scope of an interdisciplinary research project by Gramazio Kohler Research (GKR) and Agile & Dexterous Robotics Lab (ADRL) at ETH Zurich, in pursuit of the goal of bringing robots to the construction site. Over the last few years, IF has been successfully deployed in different projects [2], [3], exploring multiple strategies for localization. Prior to these projects, an earlier version of IF, the Echord dimRob [1], was utilized to explore localization with on-board sensors relative to its environment. The research

[1] A robotic total station allows for the remote measurement of vertical and horizontal angles and the slope distance from the instrument to a particular point.

[2], [3] focused mainly on on-board sensing and SLAM for the pose estimation of the robot end-effector to ensure minimal dependency on external sensing systems. Even though these methods proved to be successful, they came with certain limitations, such as in the achievable accuracy of the manipulator and the reliance on a full or partial enclosure around the robot to ensure reliable pose estimations.

This project explores a method in which an external tripod-based measuring system (an off-the-shelf robotic total station found commonly on construction sites, Figure 1) is employed to investigate the potential of localizing a mobile fabrication unit like IF with an external tracking strategy, without fixed reference points around the robot to help constrain the pose, thus eliminating the need for a full enclosure.

Figure 1. Setup exploring the use of an external measuring system in the form of a robotic total station for localization.

## 3 State of the Art

There are many methods that can be employed today for the localization of objects within a large space. The global positioning system (GPS) is used for localization on the Earth's surface, in which a network of satellites orbiting the Earth broadcast precise timing information, from which those receiving the information can calculate their position based on the timestamps of these messages. The US Department of Defence, as the developer of the system, states in [4] that the accuracy of GPS on an open field is 7.8m in the 95th percentile. A construction site, however, rarely exhibits the conditions of an open field, being mostly indoor environments, and methods that rely on GPS measurements to attain the required precision for a construction application would be more suitable for outdoor environments, such as the way the construction robotics start-up Built Robotics [5] use GPS measurements augmented with on-site base stations, fused with on-board Lidars (laser based measurements).

Recently, light detection and ranging (Lidar) devices have attracted considerable attention in the field of on-site construction involving the employment of mobile robots. Such devices measure all points in the visible environment as a point-cloud to aid localization through the use of Lidar point-cloud data, and a map of the visible environment is also needed that can either be given a priori or built simultaneously (SLAM). To exemplify, in a Mobile Robotic Brickwork project [2], an on-board laser range finder is used to scan the environment and the built structure so as to align the point-cloud data with the CAD model of the structure, and to manage the localization of IF through the creation of an enclosure around the robot to help constrain the pose.

Instead of measuring all points in the visible environment, an external measurement system, such as a robotic total station, can be used to measure the distance to a reference point – in this case, a reflector prism – in an exploration of methods to overcome limitations in positioning accuracy. A number of different approaches have been suggested involving the use of a total station for the localization of mobile robots in construction. One such approach involves placing the measurement device on the mobile hardware, which in the case of [6] was s a trolley pulled behind an asphalt paver carrying an automatic theodolite. The setup is augmented with robotic beacons placed in known locations within the surrounding environment and the theodolite rotates around its vertical axis to provide a continuous measurement of the distance to these beacons. These measurements, together with the readings from an encoder wheel on the trolley, are fused with an extended Kalman filter to obtain a position and an orientation estimate. Through the experiments conducted to date, it has been shown that an accuracy of $\pm 3cm$ in the x and y axis, $\pm 1cm$ in z and $\pm 0.1°$ in pitch and roll were achieved in 95% of the measurements. Another approach is to mount the reflector prism on the mobile hardware, as exemplified in [7], and as adopted by construction robotics start-up N-Link with the mobile drilling robot. In such systems, two prisms are mounted on the mobile base of the drilling robot and the total station carries out sequential measurements within an environment constrained by a fixed reference point. The mobile drilling robot is then localized based on the relative distances between the prisms.

In the present project, the opportunity to remove the dependency on fixed reference points within the environment is explored. For this purpose, a reflector prism was mounted on the robot end-effector (Figure 3) to allow the measurement of the point at the location of the prism from different trajectory points (instead of the robot base or at fixed locations within the workspace). The goal was to use these flexible points as reference points for the external measurement device (robotic total station), as a substitute for fixed reference points within the environment (Figure 2), hence allowing for building within an unconstrained space.

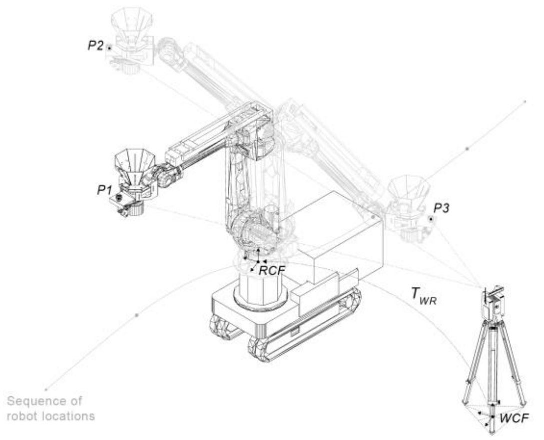


Figure 2. The substitution of "fixed reference points" with three end-effector trajectory points obtained from the mobile fabrication unit (IF).

# 4 Method

## 4.1 The setup

To localize IF using a robotic total station, a 360° reflector prism was mounted on its end effector (Figure 3), providing it with flexibility in the setting of arbitrary trajectories within the robot workspace as reference points, and ensuring a clear line of sight.

Figure 3. Reflector prism mounted on the end-effector of IF.

### 4.1.1 Hardware setup

A total station measures spherical coordinates $(\phi, \theta, d)$ in an environment that is bounded by reference points, giving the precise interpolating range. The total station used in the present project was a Hilti POS 150, together with its tablet computer POC 200 and a set of 360° reflector prisms. The POS 150 offers distance precision of $2mm \pm 2ppm$, an angle precision of $5''(\approx 0.00139°)$ and a measurement range of $\approx 1000m$.

### 4.1.2 Software setup

Communication with the IF controller in the experimentation process was based on specific libraries developed previously at ETH Zurich. All developments for localization were implemented in Python, and could be easily integrated into the overall fabrication workflow (in Rhino Grasshopper), with the most basic approach to controlling the end effector being chosen (sending poses together with speed information to the robot controller). This permitted the robot end-effector, mounted with the reflector prism, to be moved sequentially to various points in the robot workspace.

## 4.2 Three-point Localization

In this first method, the first point is chosen by the operator of the system; the second point is then located along the robot's X-Axis at distance $d$; and the third point is located along the robot's Y-Axis, again at distance $d$. The coordinates of these points $P_1, P_2, P_3$, in the robot coordinate frame, are obtained directly from the robot (Figure 2). As each of these points is also measured by the total station, the coordinates, $M_1, M_2, M_3$, are also known within the global frame. Based on the special configuration of the points, the axes of the robot coordinate frame can be inferred directly as:

$$\begin{aligned} X &= M_1 - M_2 \\ Y &= M_3 - M_2 \\ Z &= \vec{X} \times \vec{Y} \end{aligned} \tag{1}$$

While $X, Y, Z \in \mathbb{R}^3$, to simplify the next set of computations, these vectors can be normalized as:

$$\bar{X} = \frac{X}{\|X\|}, \quad \bar{Y} = \frac{Y}{\|Y\|}, \quad \bar{Z} = \frac{Z}{\|Z\|} \tag{2}$$

In the next step, the origin of the robot coordinate frame is calculated. As the direction of the axis of the robot coordinate frame in the world coordinate frame is known, the origin can be extrapolated from the measurements:

$$O_w = M_2 - P_2^X * \bar{X} - P_2^Y * \bar{Y} - P_2^Z * \bar{Z} \qquad (3)$$

where $O_w$ is the origin of the robot coordinate frame in the world coordinate frame, and $P_2^X, P_2^Y, P_2^Z$ are the $x, y$ and $z$ components of localization point $P_2$.

The transformation from the world coordinate frame into the robot coordinate frame is expressed in a homogenous transformation matrix. The $\bar{X}$, $\bar{Y}$ and $\bar{Z}$ vectors, as well as the origin $O_w$ of the robot coordinate frame are expressed in the world coordinate frame. Deriving the homogeneous transformation matrix from the robot coordinate frame to the global coordinate frame is equivalent to calculating the change of the basis matrix:

$$T_R^W = \begin{bmatrix} \bar{X} & \bar{Y} & \bar{Z} & O_w \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (4)$$

As the transformation from the global coordinate frame to the robot coordinate frame is missing, the inverse transformation is computed by:

$$T_W^R = T_R^{W^{-1}} \qquad (5)$$

Therefore, for any given point $Q_W$ the coordinates can be calculated within the robot coordinate frame by:

$$Q_R = T_W^R Q_W \qquad (6)$$

## 4.3 Arbitrary Point Localization

When using arbitrary points for localization, there is no inherent information about the orientation of the robot coordinate frame. However, similar to the point set registration problem, the two significant sets of measurements are known to differ only in rotation and translation. For the point set registration problem a multitude of algorithms exists in [10]. As previous, the coordinates of $n$ points $P_i$ in the robot coordinate frame and the $n$ measurements $M_i$ in the global coordinate frame are derived. The sum of the deviation between localization point $P_i$ and measurement $M_i$ of the same point is calculated as:

$$f(O, X, Y) = \sum_{i=1}^{n} \left\| \underbrace{O + P_i^x * X + P_i^y * Y + P_i^z * (X \times Y)}_{Localization\ Point} - M_i \right\|_2 \qquad (7)$$

With the addition of the constraints, the problem is defined as follows:

$$\begin{aligned} &\min_{O,X,Y} f(O, X, Y) \\ &X * Y = 0 \\ &|X| = 1 \\ &|Y| = 1 \end{aligned} \qquad (8)$$

The first constraint ensures that the X-axis and Y-axis of the robot coordinate system are perpendicular; while the second and third constraints fix the length of the X-axis and the Y-axis at 1, thus simplifying the formulation of the objective function. The objective function, as well as the constraints, are both non-linear, meaning that the optimization problem falls within the realm of non-linear optimization problems. Resolving the problem using such a solver as the SciPy optimization package returns a local optimum. Although brute force methods for the global optimization of non-linear functions exist, such as basin-hopping [11], by choosing the initial guess of the robot coordinate frame close to the origin, in all of the experiments, the solver converged with the global optimum. Accordingly, the result of the optimization is the robot coordinate frame being expressed within the global coordinate frame. Similarly, the calculations explained previously in the three-point method can also be applied here to obtain the transformation matrix from the coordinate frame.

### 4.3.1 Point Selection

While setting up the total station, the fixed reference points are expected to bind the area in which the measurements are to be conducted (for the accurate interpolation of the targets to be measured). When using the robot as the reference point for the setup of the total station, this aspect is violated, as only points within the robot's workspace can be given as references, and after moving the robot, all points outside this workspace are measured (resulting in an extrapolation). To minimize the error introduced during the total station setup, the optimal points within the robot's workspace are to be selected, and this can be formulated as an optimization problem, as follows:

$$X = [P_1, P_2, \ldots, P_n], \qquad P_i \in \mathbb{R}^3 \qquad (9)$$

$$\max_{X} \sum_{i=1}^{n} \|P_i\|_2^2 + \sum_{i=1}^{n} \sum_{j=i+1}^{n} \left\|P_i - P_j\right\|_2^2 \qquad (10)$$

where the first part of the sum is the distance from the origin, and the second part is the distance between points. To ensure all of the points are within the robot's workspace, the following constraints are added:

$$\begin{aligned} \|P_i - (0,0,h)\|_2 \le r, \qquad 1 \le i \le n \\ P_i^X > 0 \\ P_i^Z > 0 \end{aligned} \qquad (11)$$

where $h$ is the height of the arm above the ground ($h = 1m$ for IF) and $r$ is the reach of the robot arm ($r = 2.55m$ for IF). Furthermore, the X and Z coordinates of the points are restricted to be positive – i.e. they need to be in front of IF and above the ground. The optimization problem was implemented in Python and resolved with [12].

#### 4.3.2 Obstacle avoidance

One important aspect in the use of arbitrary points for localization is to prevent the collision of the robot arm with the structure being built. Accordingly, the heuristic algorithm used to select a point close to the desired localization point ensures that the end effector does not collide with the structure. The algorithm works as follows:

1. Set r = 10 cm
2. For each point P that does not fulfil the criteria:
    a. Set r = r + 10 cm
    b. Generate points
    c. Check criteria
    d. If all criteria are fulfilled, return point, otherwise go to step a.

Following the steps above, the points are generated as an equally spaced grid on a sphere at radius $r$ from the original point.
In step 2c, the following criteria are checked for each point:

- $Z > 0$: Point should be above ground
- $X > 0$: Point should be in front of robot
- No collision: If the end effector is placed at the candidate point, it should not collide with the structure. A bounding box approximation of the end effector is used to provide some safety margins.
- Inside the robot's workspace: The point must be within the robot's reach.
- No obstacle between the point and robot: An obstacle between the robot base and the localization point may result in a collision with the arm.

For each iteration, the first point that fulfils all the criteria is returned.

## 5 Experiments

### 5.1 Procedure

The large-scale outdoor experiment was carried out at the Hönggerberg Campus of ETH Zurich, where the target points were evenly distributed on-site between the fixed reference points (Figure 6). The fixed reference points were used to provide a ground truth to validate the precision of the approach using the flexible references obtained from the mobile fabrication unit at arbitrary locations, and by evaluating the proposed method against the existing methods that rely on the existence of fixed references for localization.

The main goal in the experiment was to see how the errors propagated over time within the proposed flexible localization method, using different end-effector trajectory points as a reference to establish the total station (global) coordinate frame (Procedure A). To demonstrate the concept, a large-scale outdoor experiment was conducted using the "arbitrary points" method, in which two different procedures were followed (Figure 4):

- Procedure A: Setting up the total station using IF (different end-effector trajectory points) as reference (Figure 4, steps 1-4)
- Procedure B: Setting up the total station with fixed reference points on site (Figure 4, steps 1-6)

As mentioned above, Procedure B was introduced to establish a global reference frame using the fixed reference points on-site to validate the precision of Procedure A (proposed flexible localization method using different end-effector trajectory points as reference).

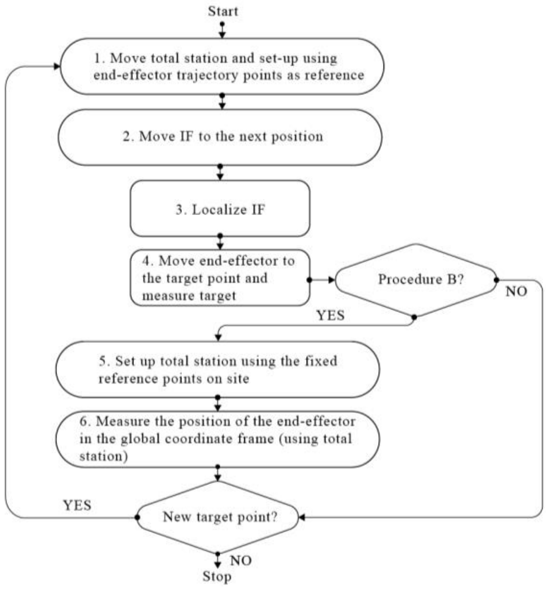


Figure 4. The full experiment flow for the acquisition of one data point.

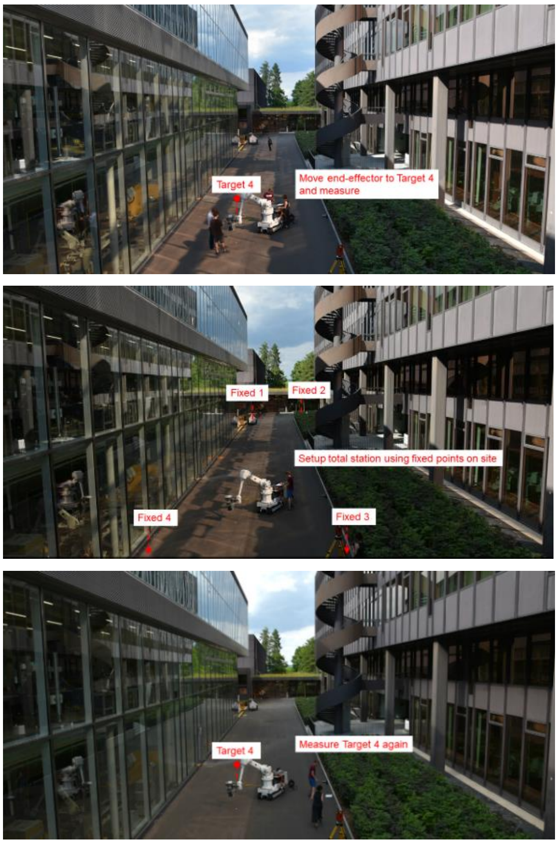


Figure 5. Steps 4, 5 and 6 of the large-scale experiment, executed for Target 4.

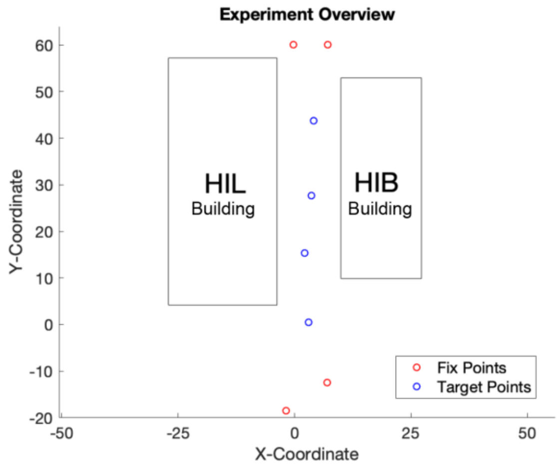


Figure 6. Large-scale outdoor experiment performed with target points distributed on site.

## 5.2 Results

The procedure was repeated five times for the acquisition of five data points.[2] Each cycle resulted in one measurement of the estimated target point, with the deviation from the planned target point calculated as:

$$D_i = P_i - M_i \tag{12}$$

where $P_i$ represents the coordinates of the planned target points and $M_i$ represents the coordinates of the estimated target points (calculated from the measurement of the end effector pose at that target point). As can be seen in Figure 7, the longer the experiment runs, the greater the deviation in the XY–plane gets, (with Procedure A, setting up the total station using IF as the reference), with an average of +-3cm and peaking at about +-7 cm at the end (Figure 7) relative to the measurements taken with Procedure B during which the ground truth is determined (for the evaluation of the proposed approach).

[2] Only four target points are marked in Figure 6. For the fifth data point, the fourth point was used a second time.

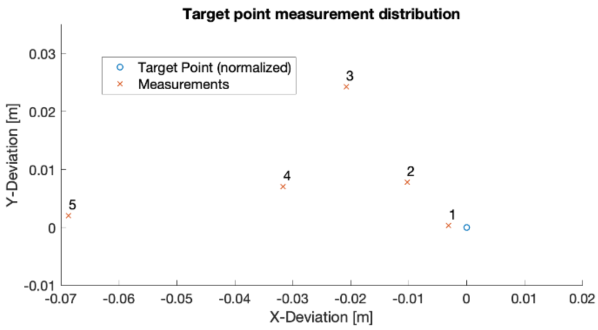


Figure 7. Deviation of the estimated points from the actual target positions in the XY-plane, at each iteration of the experiment.

## 6 Discussion and Future Outlook

The approach proposed in this paper aims to remove the need for fixed reference points for the localization of a mobile fabrication unit, with the intention being to address the problem of restricted workspaces in a defined enclosed area, and the possibility of building within an unconstrained space, as for on-site construction, the operating area is much larger than the reach of the robot arm. The approach makes use of an external measurement system for the evaluation of two methods: a three-point localization and an arbitrary point localization. Although the three-point localization approach lacks the required flexibility for a dynamic fabrication process, it carries a low computational cost and is easy to implement. In the arbitrary points method, the errors are minimized through the use of an optimization algorithm based on the sum of the squared distances between measurements. Furthermore, the points in this approach can be selected flexibly meaning that the robot can be prevented from colliding with the structure being fabricated. However, this method carries a high computational cost (as a non-linear optimization problem needs to be solved for each localization procedure) and is more difficult to implement. Both methods come with minor limitations, in that they require a clear line of sight from the reflector prism on the end-effector to the measurement device – in this case, the robotic total station.

All in all, the findings of the present study do not identify a single method that can be implemented for localization with external measurement systems. Such systems described in this research lack the perception component, which is needed for robotic fabrication in the context of construction sites, but target a precise pose estimation from point-to-point measurements (e.g. from the total station to the reflector prism on the end-effector). A future study could explore the possibility of merging this method with an on board-sensing system to increase the accuracy of global positioning.

Even though the method developed in this project was used in the context of a digital fabrication project, Jammed Architectural Structures [13] (Figure 8), the method is to be further investigated with a sensitivity analysis based on the precision of multiple devices. The goal is to introduce secondary devices, such as an iGPS system [14], to obtain ground truth for the validation of both the proposed localization method and the total station accuracy. The results of these experiments will be integrated into the present research.

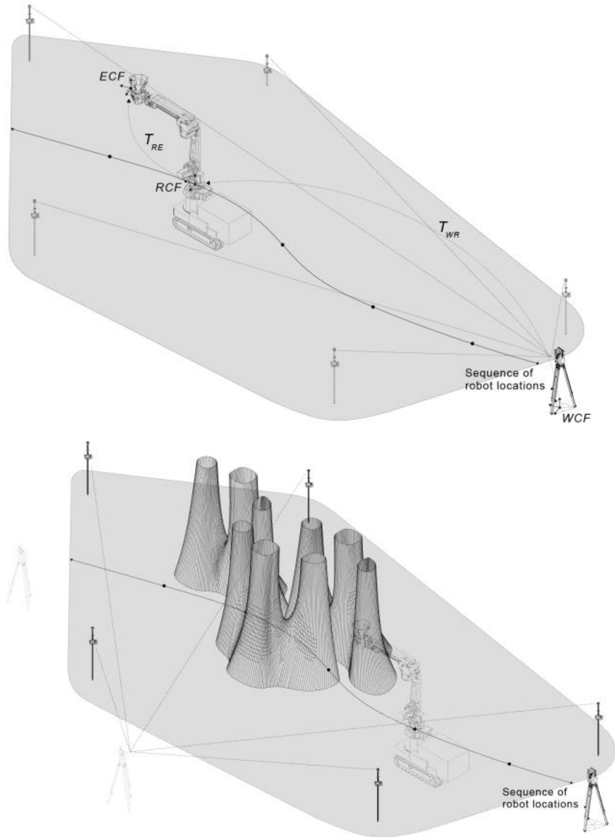


Figure 8. The method developed in this project was used in a digital fabrication project (Jammed Architectural Structures) deploying IF.

## References


[1] Helm, V., Ercan, S., Gramazio, F. & Kohler, M. Mobile Robotic Fabrication on Construction Sites: dimRob*. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 4335 - 4341. Vilamoura, Portugal, 2012.

[2] Dörfler, K., Sandy, T., Giftthaler, M., Gramazio, F., Kohler, M. and Buchli, J. Mobile Robotic Brickwork, In *Proceedings of Robotic Fabrication in Architecture, Art and Design*, Sydney, Australia, 2016.

[3] Fuentes-Pacheco, J., Ruiz-Ascencio, J., and Rendon-Mancha, J., M. Visual simultaneous localization and mapping: a survey. In *Artifical Intelligence Review*, November 2015.

[4] United States of America Department of Defense, Online: https://www.gps.gov/technical/ps/2008-SPS-performance-standard.pdf. Accessed: 07/07/2018.

[5] Built Robotics. Online: http://www.builtrobotics.com/about/. Accessed: 14/07/2018.

[6] Bouvet, D., Garcia, G., Gorham B., and Bétaille, D. Precise 3-D localization by automatic laser theodolite and odometer for civil-engineering machines. *In Proceedings of the International Conference on Robotics & Automation*, Seoul, South Korea, 2001.

[7] Halvorsen, H., Henninge, T. A., and Fagertun, K. Mobile robotic drilling apparatus and method for drilling ceilings and walls. *Patent WO2016066615A2*, 2016.

[8] Giftthaler, M., Sandy, T., Dörfler, K., Brooks, I., Buckingham, M., Rey, G., Kohler, M., Gramazio, F., Buchli, J. Mobile robotic fabrication at 1:1 scale: the In situ Fabricator. In *Construction Robotics*, 1–12, 2017.

[9] Aejmelaeus-Lindström, P., Willmann, J., Tibbits, S., Gramazio, F., Kohler, M. Jammed architectural structures: towards large-scale reversible construction. In *Granular Matter*, Robert P. Behringer, Hans J. Herrmann, 28: 1-12. Berlin, Heidelberg: Springer, 2016.

[10] Pomerleau, F., Colas, F., and Siegwart, R., A Review of Point Cloud Registration Algorithms for Mobile Robotics. In *Foundations and Trends in Robotics*, volume 4(1), 1-104, 2015.

[11] Wales, D. J., and Doye, J. P. Global Optimization by Basin-Hopping and the Lowest Energy Structures of Lennard-Jones Clusters Containing up to 110 Atoms. 1998.

[12] “SciPy.org,” Online: https://docs.scipy.org/doc/scipy/reference/tutorial/optimize.html. Accessed: 06/07/2018.

[13] “Rock Print Pavilion,” Online: https://vimeo.com/294086902. Accessed: 18/11/2018.

[14] Stadelmann, L., Sandy, T., Thoma, A. and Buchli, J. "End-Effector Pose Correction for Versatile Large-Scale Multi-Robotic Systems", RA-L/ ICRA 2019