Autonomous Construction of Separated Artifacts by Mobile Robots Using SLAM and Stigmergy

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ABSTRACT

Autonomous mobile robots equipped with arms have the potential to be used for automated construction of structures in various sizes and shapes, such as houses or other infrastructures. Existing construction processes, like many other additive manufacturing processes, are mostly based on precise positioning, which is achieved by machines that have a fixed mechanical link with the construction and therefore relying on absolute positioning. Mobile robots, by nature, do not have a fixed referential point, and their positioning systems are not as accurate as fixed-based systems. Therefore, mobile robots have to employ new technologies and/or methods to implement precise construction processes.

In contrast to the majority of prior work on autonomous construction that has relied only on external tracking systems (e.g., GPS) or exclusively on short-range relative localization (e.g., stigmergy), this paper explores localization methods based on a combination of long-range self-positioning and short-range relative localization for robots to construct precise, separated artifacts in particular situations, such as in outer space or in indoor environments, where external support is not an option.

Achieving both precision and autonomy in construction tasks requires understanding the environment and physically interacting with it. Consequently, we must evaluate the robot's key capabilities of navigation and manipulation for performing the construction in order to analyze the impact of these capabilities on a predefined construction. In this paper, we focus on the precision of autonomous construction of separated artifacts. This domain motivates us to combine two methods used for the construction: 1) a self-positioning system and 2) a short-distance relative localization. We evaluate our approach on a miniature mobile robot that autonomously maps an environment using a simultaneous localization and mapping (SLAM) algorithm; the robot's objective is then to manipulate blocks to build desired artifacts based on a plan given by a human. Our results illuminate practical issues for future applications that also need to integrate complex tasks under mobile robot constraints.

Keywords: Autonomous construction—Miniature mobile robot—Self-positioning system—Precise construction—Unknown environments

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I. INTRODUCTION

Construction automation is an interesting field focused on applying automating processes to reduce the cost of construction and/or to increase operational efficiency. Developments in robotics sciences have recently led to the use of various robotic platforms to achieve construction automation objectives, although fully automated construction is still a dream of civil engineers. Robotic developments have shown that robots could potentially perform construction tasks where human presence is impossible, undesirable, or intensively expensive, for instance, construction in hazardous areas after natural or man-made disasters such as earthquakes and nuclear accidents; construction under difficult physical conditions such as undersea or outer space locations; and construction where in area that are not readily accessible to humans or that require an initial structure to prepare the environment for human arrival. Robots can be used to build these structures for particular situations in the autonomous mode without explicit human intervention or with some levels of planning interaction conducted with a human supervisor.

Generally, a robot performing autonomous construction has to adapt itself to the sensed environment, make decisions regarding the execution of its task, and replan when its task is not executable. Mobile robots represent one type of robotic system that could be used for construction automation. Applying mobile robots to construction opens new approaches in this field. For instance, building large structures without being confined by dimensions is a challenge for current technologies; for example, we might need huge and expensive fixed-based fabricating systems (e.g., 3D printers) to build giant structures. Capabilities of mobile robots, however, allow them to create objects without fixed-base system constraints (e.g., size of the printer's frame constraint). Similar to social insects, such as ants, a group of mobile robots can work cooperatively, as a collective system, to efficiently build large-scale.

In contrast to these advantages, mobile robots, by nature, do not have a fixed referential point and their positioning systems are not as accurate as fixed-based systems. Existing construction processes, like many other additive manufacturing processes, are mostly based on precise positioning, which is achieved by machines that have a fixed mechanical link with the construction and rely on absolute positioning. Therefore, mobile robots have to compensate for this weakness with new technologies and/or methods to supply precision for construction processes. Although equipping robots with external tracking systems (e.g., GPS, camera) provides an accurate positioning system, but we aim to implement and study localization methods based on self-positioning system to autonomously handle construction tasks, especially where external tracking systems is are difficult to access and are expensive (e.g., undersea). On the other hand, the accuracy of self-positioning system is not sufficient to handle construction processes; therefore, we aim to combine it with short-range relative localization to provide the required precision for construction of structures spatially separated from one another, which we refer to here as separated artifacts.

In this paper, our goal is to develop a construction system by which robots are able to build separated artifacts. We evaluate our approach with a miniature autonomous mobile robot and simple blocks in unknown environments. The robot's objective is to build the artifacts using both the simultaneous localization and mapping algorithms (SLAM) and stigmergy based on a human-prescribed blueprint. In fact, it employs SLAM using the LIDAR scanner to autonomously map an environment and determine the current robot position. The robot's end effector is equipped to many IR-sensors that allow it to sense previously placed blocks in order to place subsequent blocks; this approach is commonly referred to as stigmergy [1].

In Section II, related work is discussed. The scenario and assumptions, robot hardware, and control are provided in Section III. The results and discussion are presented in Section IV. Finally, in Section V, we conclude for this study.

II. RELATED WORKS

In this section, we are primarily reviewing research that employs mobile robots for autonomous construction based on positioning systems, robot platforms, and materials. Obviously, precise positioning systems are necessary for most systems to support construction processes. At present, an external localization system could be employed to provide accurate systems for construction. In the research conducted at ETH Zurich, four quadcopters are exploited to construct a brick-like tower. They benefit from an external real-time camera system to guide robots to pick up and deposit objects according to the given blueprint [2]. Lindsey *et al.* [3] used a team of quadcopters to assemble the cubic structures with particular self-assembling rods . The VICON motion tracking system is used to estimate the position and orientation of the picked objects and aerial vehicles states. It provided position feedback at 150 Hz with marker position accuracy on the order of a millimeter. Moreover, VICON is used by ground robots to build roofed structures [4].

Another general external system is the GPS used by a robotic excavator with centimeter resolution allowing them to determine position accurately and then to control the motion of the robots [5]. In [6], the ROCCO robot was developed to assemble heavy blocks in industrial buildings with standardized layouts. It was equipped with digital angular encoders and an external global position sensor (telemeter) correct error. In [6], a method was demonstrated in simulation by which robots are able to build 2D structures of desired shapes by blocks. A robot acts as a stationary beacon to help other robots find its position. In [7], robot placed blocks of alternating color along a straight line starting with a pre-placed seed block located underneath a beacon. Although using external system improves the positioning system capability, many additional localization devices are required, which might be impossible or very expensive to provide, for example, in outer space or undersea construction. In contrast to these works, the robot is completely autonomous in our work and does not rely on any motion-capture systems or external localization systems.

However, some robots applied short-range relative localization for construction. Werfel *et al.* [8] present 3D collective construction in which enormous numbers of autonomous robots build large-scale structures. They employed a ground mobile robot that was inspired by activity of termites. Robots climb on the structure to drop passive solid blocks on top of it. They just use six active infrared (IR) sensors to recognize white stripes on the blocks and then determine their path and final destination. Novikov *et al.* [9] have built 3D shape structures by using deposition amorphous material with mobile heads. This method allows an object to be printed independent from its size of the object.

Stroupe *et al.* [10] present construction by two platform robots SRR and SRR2K in an outdoor environment. Each rover is holonomically equipped with a forward-facing stereo pair of cameras and a four degree-of-freedom arm. A triple-axis force-torque sensor on the gripper helps the rover maintain coordination for transporting and placing rods. This model provides high-precision manipulator placement by comparing the observed position of beam markers on the end effector with the obtained kinematics position of the end effector.

In some research, self-alignment methods have been used to tackle substance alignment and attachment restrictions. For instance, bricks are made from expanded foam, with physical features to achieve self-alignment and magnets for attachment [11]. In [12], self-alignment cubic modules are used to build structures. The special assembler robots manipulate and transport these modules. In [13], a novel robot used bidirectional geared rods and connectors to build a truss structure. In conclusion, using only the short-range relative localization limits construction to a local place because robots need to look at the local configuration of the building material to determine where to add additional materials.

Magnenat *et al.* [14] used a miniature autonomous robot with a magnetic manipulator to grasps ferromagnetic self-alignment blocks. This robot also has the LIDAR and camera on top. It used the odometry and laser data to perform SLAM and employed the front camera and proximity sensors to provide the required data for dropping blocks. The goal of this research was to use ten blocks to build a simple tower. We advance this research by studying the precision of using both a short-range relative localization and a self-positioning system for separated artifacts.

III. SYSTEM DESCRIPTION

A. Scenario and Assumptions

As overviewed in the Introduction, the goal of this experiment is to build separated artifacts based on a blueprint by a human in an unknown environment. We assume that the initial position of the robot is also the location of a block repository. We put a new block at the repository for each step of construction. The robot has to detect the block and align itself with respect to the block to able to pick up the block at the correct position of gripper.

The arena is a 200 cm × 100 cm rectangle with a flat surface that contains few obstacles. Note that the environment is unknown for the robot, and SLAM is used to inform the robot of its position and to map the environment for path planning as well. The artifacts, as illustrated later, are composed of simple polystyrene blocks with an attached stripe of ferromagnetic metal on the lower part of the body (Figure 1). Each block is 6 cm in length, 6 cm in width, and 18 cm in height, and it weighs approximately 20 g. The size and weight of the block are chosen to satisfy the requirements of the robot's gripper and the LIDAR.

After grasping the block, the robot moves toward the destination point. The path-planning algorithm determines the global path to the destination. It also sets the local path planning during its movements to avoid collision with dynamic obstacles and to correct the path based on the robot's improved position. The first block of the artifact will be dropped after the robot fine-tunes its position using the accurate movement behavior.[1] The robot returns and takes a new block from the repository. Now, the robot is ready to drop the second block of the artifact. The robot drops the second block beside the first block using stigmergy. In this section, we explained the construction scenario and assumptions. In the next sections, we first describe the robot hardware and then provide the details of the control system, including low-level behaviors and control architecture.

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[1] See section 3-3-2

Figure 1. Polystyrene blocks are used for the experiments.

Figure 2. The MarXbot consists of the gripper, LIDAR, computer board, base modules.

B. Robot platform

For the experiment, we used a miniature and modular robot called marXbot [15] (Figure 2). The robot is 17 cm in diameter and 18 cm in height. It consists of four modules as follows:

Base: The non-holonomic base has 2 degrees of freedom (DOF), a 38Wh lithium polymer battery, and 24 proximity sensors.

Gripper: The 3 DOF magnetic manipulator consists of a magnetic switchable device to grasp ferromagnetic objects. This module has 20 proximity sensors for the alignment usage.

Computer board: This module includes the main computer based on a 533MHz Freescale i.MX31 with 128MB of RAM and running LINUX.

LIDAR: The 360° laser distance scanner (Neato LIDAR < $100) perceives walls and obstacles.

C. Control system

I) Control architecture

The control architecture, shown in Figure 3, consists of several layered modules. At the top, the *builder planner* serves to execute an overall construction of separated artifacts by generating a sequence of high-level sub-goals. These sub-goals either take the form of target poses for robot movement, which are delegated to the *navigation* block, or block manipulation sub-goals (such as *pickup* and *place*), which are delegated to the *middle planner*.

Navigation is implemented through a collection of ROS nodes, including navigation (Move_base[2]) and SLAM (Hector_mapping[3]) packages. The SLAM package receives the data from the LIDAR to map the environment and localize the robot. The navigation package obtains the map and positioning information from SLAM to direct and set the reliable paths for the mobile robot from the current position to the goal position. To physically move the robot, *navigation* in turn invokes low-level behaviors that have been pre-programmed using the ASEBA software architecture [16], which runs directly on the robot's microcontrollers.

The *middle planner,* implemented using state-of-the-art AI planning technologies [17], renders the robot fully autonomous in its manipulation of blocks in the environment. For each manipulation goal (pickup, drop, place-adjacent-to), the robot accesses a (pre-computed) conditional plan that iteratively selects among low-level task executions (e.g., approach-to-within-manipulation-distance, align-gripper-angle, grasp-block). Each of these low-level tasks is implemented as a finite state controller that, at 5Hz, senses using the gripper infrared and actuates the treel[4] and gripper motors. Due to sensory inaccuracies and environmental imperfections, the low-level tasks are not deterministic in their effects. For instance, a brief mis-measurement of infrared distances caused by fluctuations in ambient lighting could cause the align-gripper-angle controller to over-rotate the gripper such that the robot loses sight of the block that it is aligning with. When such unintended effects occur, the robot's conditional plan gracefully recovers by selecting the next appropriate task. In essence, the conditional plan composes a complex and dynamic sequences of tasks that is theoretically guaranteed [18] to eventually bring the robot to its manipulation goal.

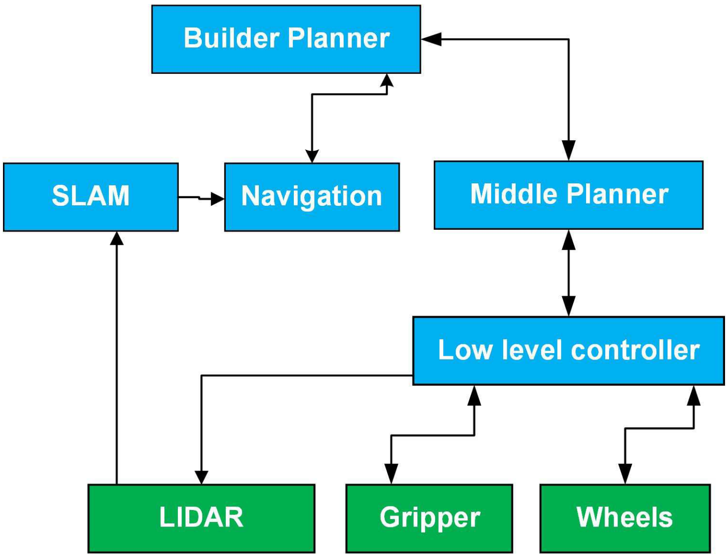

Figure 3. Control architecture in which green and blue boxes represent hardware and software layers, respectively.

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[2] Move_base is a 2D navigation stack that receives information from sensors and a goal pose and then directs the mobile base by determining safe speed and reliable paths.

[3] Hector_mapping is a SLAM algorithm using LIDAR systems such as the Hokuyo UTM-30LX. The system has been used on unmanned ground robots, unmanned surface vehicles.

[4] Treel refers to a combination of a wheel and a track.

II) Low-level behaviors

Pick-up: The pick-up behavior has to accurately grasp blocks because a misaligned block will add errors to all subsequent operations. As illustrated in Figure 4, the middle planner generates a sequence of movements. At the beginning, the robot turns to face the repository. It uses both the ROS navigation and accurate movement behavior to align itself at the right angle; then it starts to find the nearest block (1). The robot then uses front infrared sensors of the gripper to tune the distance in respect to the blocks (2). Next, it rotates 90 degrees rightward, and the gripper rotates in the opposite direction (3), which situation helps the robot align itself laterally. Using the front infrared sensors of the magnetic gripper also helps the robots to align the block at the center of the gripper (4). When the block is centered, the robot performs a 90-degree leftward rotation while the gripper rotates in the opposite direction (5). It then moves forward and rotates a few degrees at a time to touch the block at the corner of the magnet position (6). When the robot touches the blocks, it grasps it and lifts up the gripper; this time the block is well aligned (7).

Traveling: This behavior consists of raising the gripper in order that the attached block and gripper do not interfere with the robot movements and SLAM.

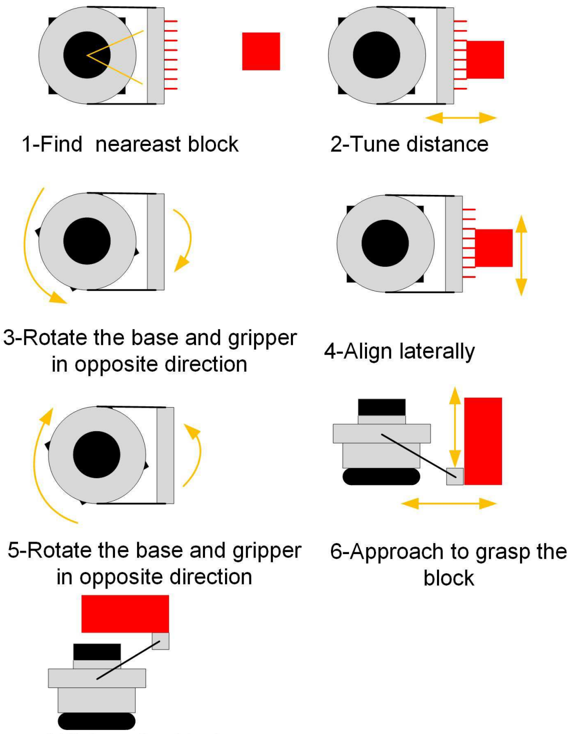

1-Find nearest block
2-Tune distance
3-Rotate the base and gripper in opposite direction
4-Align laterally
5-Rotate the base and gripper in opposite direction
6-Approach to grasp the block
7-Pick up the block successfully

Figure 4. The movement sequence to pick up a block.

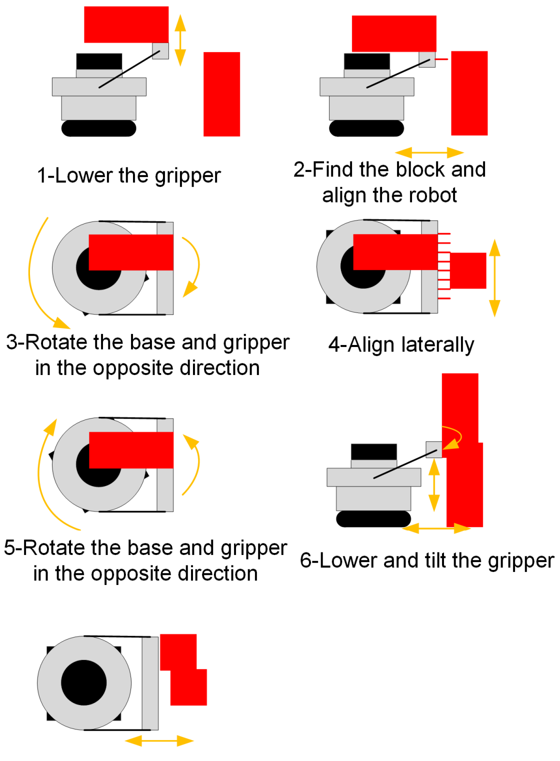

1-Lower the gripper
2-Find the block and align the robot
3-Rotate the base and gripper in the opposite direction
4-Align laterally
5-Rotate the base and gripper in the opposite direction
6-Lower and tilt the gripper
7-Push the block

Figure 5. The movement sequence to drop a new block adjacent to a placed one.

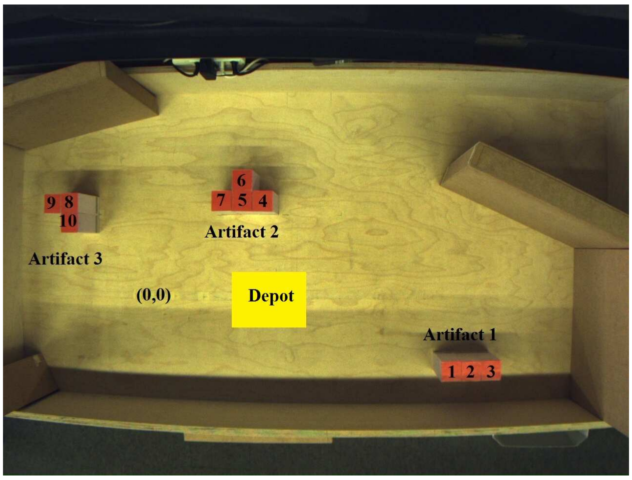
Accurate movement: This behavior occurs in two modes to move the robot precisely. When the robot approaches a destination point, this behavior moves the robot to put it in the precise position using a PID controller. In the first mode, it rotates and moves to correct its position in the X axis. The robot then rotates 90 degrees and moves to correct its position in the Y direction. Finally, it rotates to reach the goal yaw angle. In the second mode, the robot only rotates to correct its yaw angle. Depending on the situation in the planner request, the robot will use either the first or second mode.

Drop/Place-Adjacent-To: This behavior consists of dropping a block either in the first place of the artifact or directly adjacent to existent blocks. To build an artifact, the robot has to drop its first block. Thus, it simply lowers the gripper after finding the precise position and then disengages its magnetic switchable device. It then lifts its manipulator slightly and moves back for a short distance. For the remaining blocks of the artifact, the robot goes toward the artifact (1) and scans for it using the magnetic gripper's IR sensors. The robot computes the distance to the artifact and moves accordingly to tune its position (2). Then it rotates 90 degrees while it rotates the gripper in the reverse direction with the same angular speed. In this position (3), the robot aligns itself laterally and then finds the left edge of the placed block to drop the new one exactly beside it (4). The robot performs a 90-degrees leftward rotation while the gripper rotates in the opposite direction (5). It then moves forward, lower, and rotates the gripper by a few degrees at a time to avoid collision with the other blocks (6). It then lowers its gripper slightly and moves back a short distance. Finally, the robot tilts the gripper and moves forward to push and line up the block (7).

IV. RESULTS AND DISCUSSTION

We employed the marXbot for the two types of experiments. First, the robot places three blocks based on given positions to study the precision of SLAM. In the second type, we employed both stigmergy and SLAM to build several separated artifacts, each made up of composed by several blocks. Five trials were carried out for each type of experiment. Figure 6 illustrates the construction of artifacts through some snapshots at the different steps. After finishing artifact construction, we took a photo to measure construction performance. We extracted the red color through image-processing methods to compare the performance of each experiment with the ideal block arrangement. In the ideal block arrangement, we assumed SLAM and stigmergy were perfect, and artifacts were being built exactly based on the given map. Using this model, we can measure the translational and rotational errors of the blocks on the plane as illustrated in Figure 7. The graphs in Figure 9 and Figure 10 show these absolute errors for the two experiments. In the first experiment, the robot only drops blocks B1, B4, B8 (the first block of each artifact) using SLAM. The important error of placement based on SLAM, of one third of the block size, shows that we cannot use this positioning technique to build artifacts made of several blocks. If the robot employs only SLAM, the important positioning error will cause collisions among blocks or gaps between blocks of the artifacts. Nevertheless, the robot can find the approximate position of construction and then apply other methods (e.g., stigmergy) to successfully accomplish the construction.

For stigmergy, the robot uses infrared sensors to align itself with respect to the blocks that are already part of the artifact. Because the artifacts are not fixed to the ground, the dropping operation may cause a displacement of the existing blocks. As illustrated in Figure 10, the average errors of stigmergy for blocks B4 and B8 (first block of the second and third artifacts) are different from the errors measured after using only SLAM (see Figure 9). This shows that the sigmergy action moved these blocks. This means, for instance, that when the robot pushed the block to align it, it also pushed previously-placed blocks because of the errors in stigmergy positioning. Indeed, if the robot could apply a perfect stigmergy, we would expect to see the same precision for other blocks of the artifact as we saw for the first block.



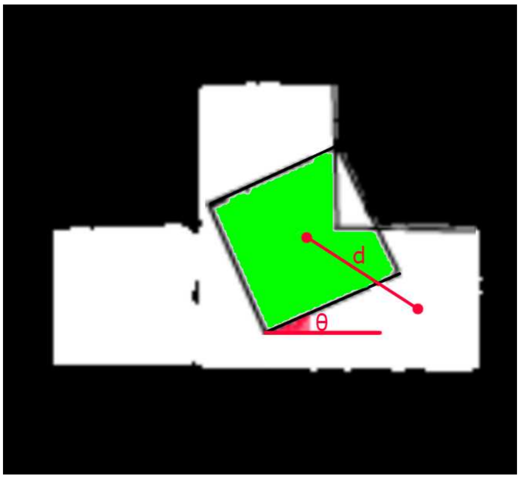


Figure 6. Ideal arrangement of the blocks is shown for the three artifacts. A comparison of built artifacts with this ideal arrangement provides the construction performance results. The robot starts from the (0,0) point to take a block from the repository. The numbers on the blocks point to the numerical order for the construction.

Figure 7. The processed image of the second artifact and measuring translational and rotational errors for the fourth block; *d* shows the distance between center of the squares, and *θ* shows the angle between the lower edges of the squares. Green color also depicts the overlap area between the fourth block and the second artifact.

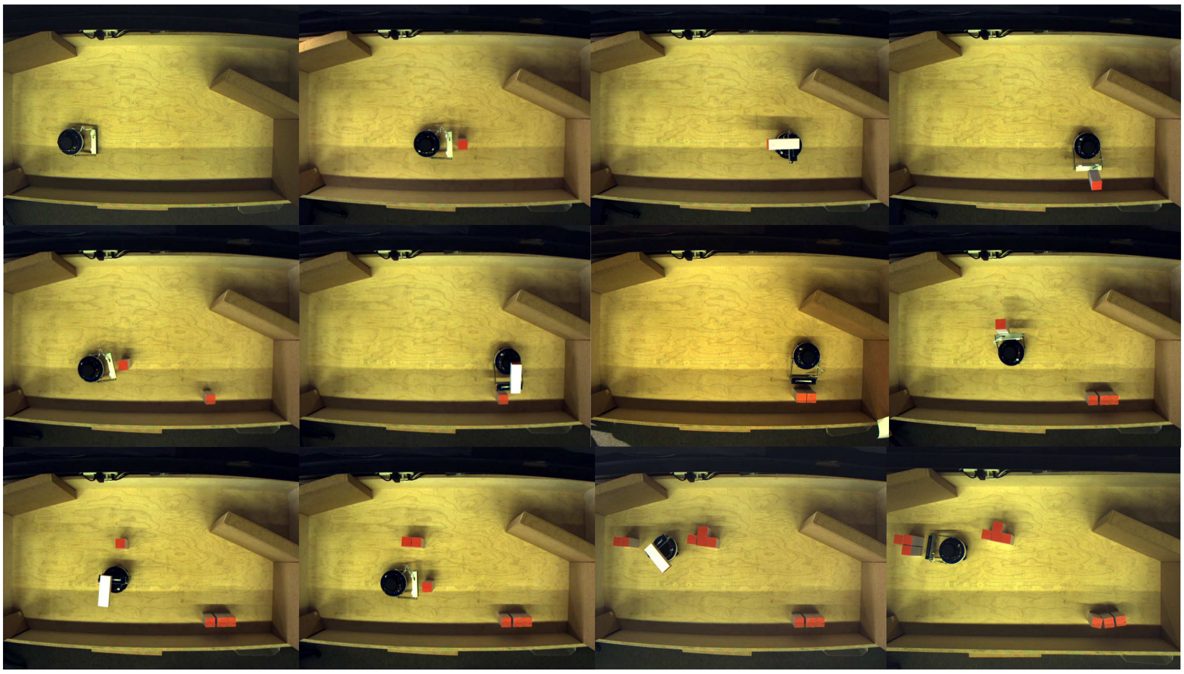


Figure 8. Image sequence of artifact construction

Overall, stigmergy could improve or weaken the precision. If the artifacts were fixed to the ground, the robots could be able to use force sensing to push the blocks without influencing the precision of the next dropping steps. Moreover, the minor difference of the translational and rotational blocks errors for each artifact shows that the building artifacts are not sensitive to the final shape or to the number of blocks used in these experiments.

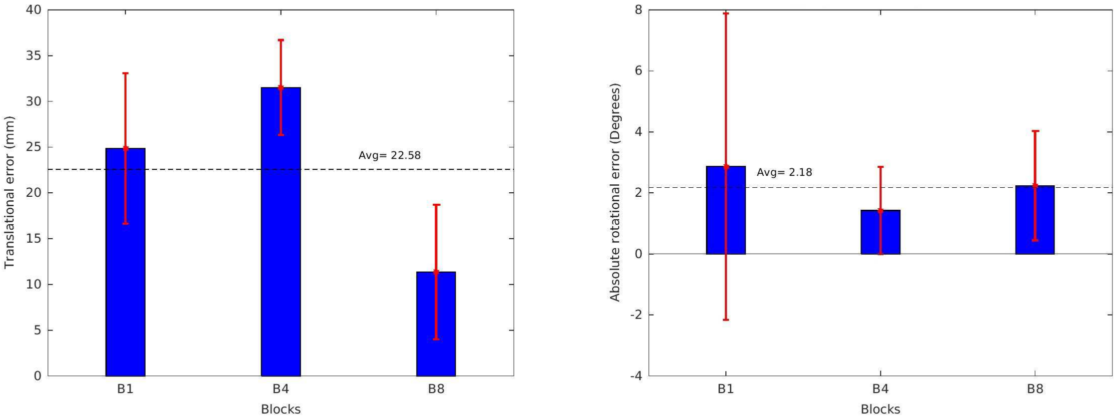


Figure 9. The left graph shows the translational error and the right graph shows the rotational error when the robot drops the first, fourth, and eighth blocks using just SLAM.

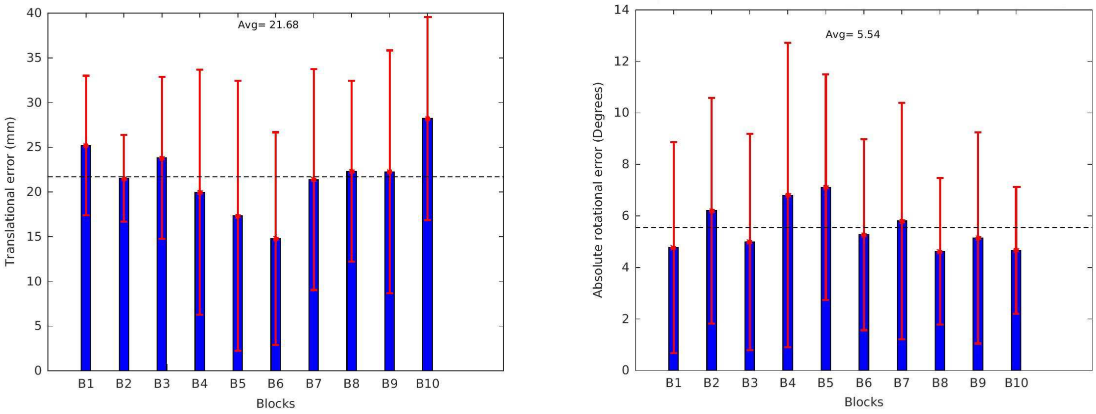


Figure 10. The left graph shows the translational error, and the right graph shows the rotational error when the robot is supposed to build the artifact with SLAM and stigmergy.

Finally, we measured the surface of each ideal artifact that is occupied by blocks placed by the robot. Ideally, the overlap percentage between the blocks and the given blueprint has to be a 100%. Figure 11 shows the overlap percentage for two construction types: single separated blocks or separated multiple-block artifacts. Note the average percent of the single-block construction is 57.88%, but it is 73.53% in artifact construction. This increase of performance does not mean that multiple-blocks artifacts are placed more precisely, because adjacent blocks can compensate for the positioning error for the global covering of the artifact surface. This increase of performance only shows that stigmergy enables the construction of more coherent artifacts.

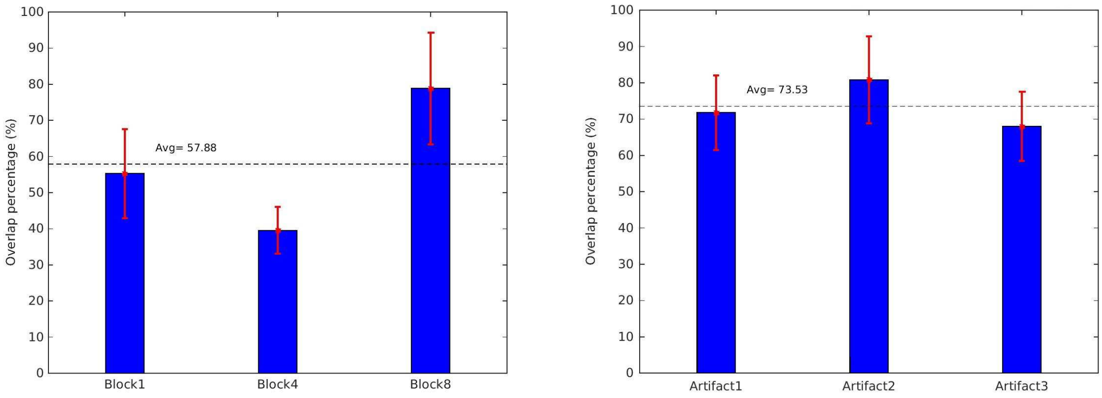


Figure 11. The left graph depicts the overlap percentage for dropping blocks based on the using SLAM, and the right graph depicts the overlap percentage for building the artifact based on using SLAM and stigmergy.

This section provided an analysis of the precision achieved by a mobile robot in building separated artifacts using SLAM and stigmergy. The SLAM algorithm was used as a localization and mapping method by a miniature mobile platform in an unknown environment. In our experiment, we have a translational error of about *21 mm* (one-hundredth of the diagonal of the environments) in a static environment using a miniature robot with a low-cost LIDAR. It is difficult to evaluate how this error will scale in a real environment because the SLAM accuracy depends on many factors; environment dimensions will clearly impact precision, as larger distances will generate larger measurement errors. The quality and quantity of landmarks also impacts the estimation of the position by the SLAM algorithm. A dynamic environment can also cause a loss of precision, as dynamic obstacles can hide interesting landmarks. Finally the quality of the sensor for distance measurement impacts the whole system directly. Obviously, there is a need to further develop the sensory system and SLAM algorithms for complex artifacts in real and large environments. Despite a lot of progress in the past decades in the SLAM field, high-precision applications are still challenging. For the time being, SLAM could help to find approximate construction sites and then the robot could use other methods to follow the construction, such as stigmergy as used in this research.

In this research, we applied stigmergy based on a pure IR-sensing system while the mechanical stigmergy can be more suitable to place the blocks. Today, companies are designing and manufacturing prefabricated components to increase construction speed and efficiency. New prefabricated components could be designed and made for robotic use in automated construction. For example, components with male–female connectors allow for automatic assembly in a more robust way [11]. Developing construction methods based on mechanical stigmergy or using force-sensing systems could provide a new way to place components in a more reliable and precise way.

Autonomous construction is also a complex application in which many failures can occur. These failures can propagate from one step to another, for instance, if the robot incorrectly grasps the block, it could destroy the built structures. Thus, it is important to detect and correct faults. We performed fault detection for middle planner, which is responsible for the planning low-level behaviors (pick up, drop, place-adjacent-to); however, we need to improve the builder planner to take high-level decisions for failures caused during construction.

V. Conclusion

This paper presents an autonomous construction system for building separated artifacts with simple blocks. We used a miniature mobile robot that autonomously mapped an environment using a SLAM algorithm and then manipulated blocks to build desired and separated artifacts. Our approach was based on the combination of two methods: a self-positioning system (SLAM) to find the construction place in an unknown environment and stigmergy to build coherent artifacts. The control system allowed the robot to perceive and pick up the block, move toward the construction place in an unknown environment, and drop the block based on a human-prescribed blueprint. We observed that, even in an ideal environment, positioning using SLAM is not sufficiently precise. This task still requires improvement in sensing technology. We also observed that stigmergy allow the creation of coherent constructions. The process analyzed in this paper, based on mobile blocks and sensing stigmergy, could be improved by having blocks fixed when dropped and employing mechanical stigmergy.

As a result, in future works, we are focusing on developing robot hardware and improving the SLAM algorithm. We also plan to develop stigmergy and use force-sensing systems for mechanical stigmergy. Thanks to stigmergy and hardware development, robots could be used to build complex artifacts such as a multi-layer wall with prefabricated components.

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