Adaptive Construction Behavior in Robot Swarms

Yara Khaluf

Department of Information Technology
Ghent University
Ghent, Belgium
Email: yara.khaluf@ugent.be

***Abstract*—In this paper, we investigate the collective behavior of a robot swarm that emerges in constructing walls for isolation purposes. Collective construction is one of the highly required behaviors for the future applications at which robotics systems are planned to be deployed. The construction task is performed using a swarm of homogenous robots. We, furthermore, present a probabilistic approach that allows us to design an adaptive construction behavior. Our results are verified using physics-based simulations.**

***Keywords*–Robot swarms; Collective construction; Adaptive behavior.**

I. INTRODUCTION

One of the fascinating self-organized behaviors in nature is collective construction, that is observed by many social insects such as ants and bees [1]. Collective construction refers to the ability of simple individuals to achieve the construction of complex structures in a self-organized manner by following a set of simple rules. A prominent example can be found by termites, which are able to build complex and huge mounds without any detailed plan. Termites live in societies where the collective power outstrips that of the individuals. They communicate between each other directly and indirectly through their environment (Stigmergy) in order to take decisions related to depositing their pieces of building material, see [2]. Swarm robotics is a promising approach in which a large number of simple robots collaborate to achieve a goal beyond the capability of an individual robot, see [3]. Swarm robotics was mainly inspired by natural swarms and has inherited their advantages including fault-tolerance, scalability, and flexibility. Those advantages allow swarm robotics to provide an efficient solution for a wide range of applications, in which constructing particular structures may be a fundamental task.

In this paper, swarm robotics is used to achieve a collective behavior that results in constructing a wall to separate a working arena in two parts. This task can be used in real scenarios to prevent the access from one part of a particular arena to its another part or to isolate dangerous parts. Construction tasks can be an important part of military tasks, agriculture tasks, civil tasks, and others. We start by designing a self-organized construction behavior. Afterwards we present a probabilistic approach in order to turn our behavior into an adaptive one that can deal with the various dynamics of the environment, e.g. recognizing the construction progress and thus the end of a construction task or the need to isolate a new part of the arena by constructing a new wall. The rest of the paper is organized as in the following: Section II introduces the wall construction problem and presents the performance metrics (quality metrics) used in measuring the quality of the obtained solutions. Section III is dedicated to discuss the related work that has focused on constructive behaviors in natural and robot swarms. The construction behavior of a robot swarm is described in Section IV, in which both the general and the adaptive construction behaviors are presented. A set of physics-based simulations and the discussion of their results are presented in Section V and the paper is concluded in Section VI.

II. PROBLEM DESCRIPTION

A homogeneous swarm of N robots – all are foot-bots having the same hardware – is used to build a wall that isolates an undesired (dangerous) part of the arena from the rest of the arena. The wall should be constructed in a way that access is prevented between the two arena parts. The location at which the wall is required to be constructed is referred to as the construction area, which can be indicated using specific environmental parameters. In our scenario, the construction area is indicated by using a black strip on the floor. Furthermore, we assume that M building blocks (cylinder shaped) are scattered initially at the safe side of the arena, where M is equal to or greater than the amount of blocks required to build the desired wall. The building blocks are identical and the block can be transported using a single robot. The required height of the wall is equal to the height of a building block. Thus, the wall is built using a single layer of blocks i.e., no vertical building is needed. Since no exact notions of the building process are encoded in the robots' behavior, constructing the required wall represents a serious challenge.

Our goal, as mentioned above, is to isolate a dangerous part of the arena from a safe one. Therefore, the constructed wall should prevent intrusions by being as compact as possible. Moreover, it should provide the maximum coverage possible over the boarder between the two sections of the arena, and finally, it should consume as less building blocks as possible to preserve such blocks for potential construction tasks in the future. We define three performance metrics to measure the quality of the wall that needs to be constructed along the y-axis of the arena, see Figure 1 for illustration:

- **The wall thinness** is defined as:

$$W_{thinness} = \begin{cases} 0 & \text{if } M = 0, \\ 1 - \dfrac{\sigma(X)}{x_{max} - x_{min}} & \text{otherwise} \end{cases}$$

  where σ is the standard deviation and X is the set of the x coordinates of the building blocks within the construction. x_{max} and x_{min} are the maximum of the

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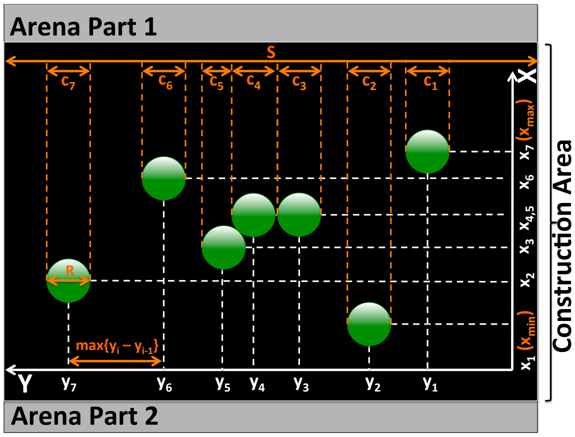


Figure 1. Illustration of the quality measures used in the performance metrics.

x coordinates and the minimum of the x coordinates, respectively. The thinness measure takes its values in the range $[0, 1]$ and an optimal solution is the one which maximizes this measure and thus leads to build a thiner wall.

- **The wall compactness** is defined as:

$$W_{compactness} = \begin{cases} 0 & \text{if } M < 2, \\ \dfrac{max\{y_i - y_{i-1}\}}{R} & \text{otherwise} \end{cases}$$

Where $max(y_i - y_{i-1})$ is, as illustrated in Figure 1, the maximum distance between two consecutive blocks on the y-axis. R is the diameter of a construction block. Compactness is best when it is close to 1. A value lower than 1 means that the maximum distance (projected onto the y-axis) between the center of the blocks is smaller than R. Whereas, a value larger than 1 means that the maximum distance between the center of the blocks is smaller than R.

- **The wall coverage** is defined as:

$$W_{coverage} = \begin{cases} 0 & \text{if } M = 0, \\ \dfrac{\sum_{i=1}^{\#placed\ blocks} c_i}{S} & \text{otherwise} \end{cases}$$

Where c_i is the diameter projection of the i-th block in the construction area on the y-axis (in the sum we remove the overlaps of the projections) as shown in Figure 1. S is the size of the construction area along the y-axis. Coverage takes values in $[0, 1]$ and an optimal solution is the one which maximizes this measure and thus leads to a larger coverage.

III. Related Work

Collective construction is a well-known behavior in natural swarms such as social insects, in which complex structures are achieved in a self-organized manner. Authors in [4] have reviewed some of the basic mechanisms used by social insects to build structures such as mounds by termites, brood structures in honey bees, and others. Other examples can be found in [5] and [6]. Furthermore, several authors tried to formalize the construction behaviors observed in nature in models, such as in [7] and [8].

In swarm robotics and based on its significant importance, collective construction was tackled in several works. In [9], the authors proposed a system of 20 small bulldozers employing simple rules to level the ground at a lunar construction site. In [10], the authors have introduced a minimalist solution inspired from the behavior of the Leptothorax tuberointerruptus ants to build a defensive wall using two templates which were created once using a white strip and second using halogen lights. The presented approach is relatively inflexible where turning angles and particular traveling distances are hard coded. The authors in [11] have tackled the problem of constructing a wall in which blocks should be of alternated colors and robots communicate to agree on the next feasible color of the building block. This work focuses on the role the communication plays in coordinating the behaviors of the robots. This is illustrated by showing that exchanging the color of the last block reduces the attempts to place a block of the same color as next. Authors in [12] have developed a mathematical model based on a particular species of ant called blind bulldozing, for the purpose of clearing an open area out of rocks. In [7], the authors considered construction problem without addressing the issue of generating pre-specified structures. Some works have presented approaches, in which the building blocks are the mobile robots themselves as in [13] and [14]. In these approaches, having a global knowledge about all agents is likely required, which on the other hand restricts the ability of building a self-organized and scalable system.

Differently from the works mentioned above, the approach presented in this paper is a self-organized, scalable and adaptive approach for robot swarms in which robots work in a full autonomy. Neither building instructions nor global knowledge are available and the quality of the constructed wall is assessed using the above-mentioned set of performance (quality) metrics.

IV. The Construction Behavior

In this section, we describe the behavior of the individual robots that emerges in constructing walls to isolate areas for preventing undesired access. The design starts from the microscopic level (individual level) at which we define the rules applied by the robots and ends up at the macroscopic level (swarm level) at which we measure the overall performance. Characterizing the link between the microscopic and the macroscopic behaviors is one of the main well-known challenges in swarm robotics, in general, and particularly in this task, where the macroscopic behavior is restricted to specific criteria. In the following, we are presenting two behaviors: the general construction behavior and the adaptive construction behavior.

A. *The general construction behavior*

In the general construction behavior, we focus on designing a robot behavior that leads to construct a wall for isolation in an unknown environment. Robots which are applying the general construction behavior perform the following tasks: searching for building blocks; gripping the found blocks; navigating to the construction area; and finally unload the blocks and tune the wall before they start again to search for new building blocks. Figure 2 shows the a finite state machine (FSM) that describes the behavior of the individual robot on the microscopic level. The robot starts initially in the searching state. In this state, it wanders randomly around the part of the arena at which the building blocks are scattered trying to find a block. Robots are required to avoid gripping blocks that are already gripped by other robots (e.g. using broadcasts). As soon as a block is found, the robot comes closer to the block attempts to grip it. In case the gripping was successful, the robot starts moving towards the construction area to place the building block. While moving, robots avoid other robots and objects using both their camera and proximity sensors. As soon as the robot reaches the construction area, it aims to unload the building block at the best possible position, taking into consideration other building blocks that are already unloaded. Achieving an efficient unload that meets the quality measures defined above is a non-trivial task. In the implemented construction behavior, we allow the robots to exploit the moveable gripper for adjusting the unloading position so that the distance to the nearest block with no two direct neighbors is minimized. This behavior allows to increase the compactness of the constructed wall and decrease its thinness. After finish unloading the building block, the robot switches to a special state referred to as the wander state. This state is identical to the searching state, except that robots at this state are not allowed to grip building blocks. This state is activated each time a robot unloads a building block and while the robot is moving near to the construction area for preventing the robots to grip blocks that are already placed as a part of the wall. The robot stays in the wander state for a particular time before it switches back to the standard searching state and becomes again able to grip blocks.

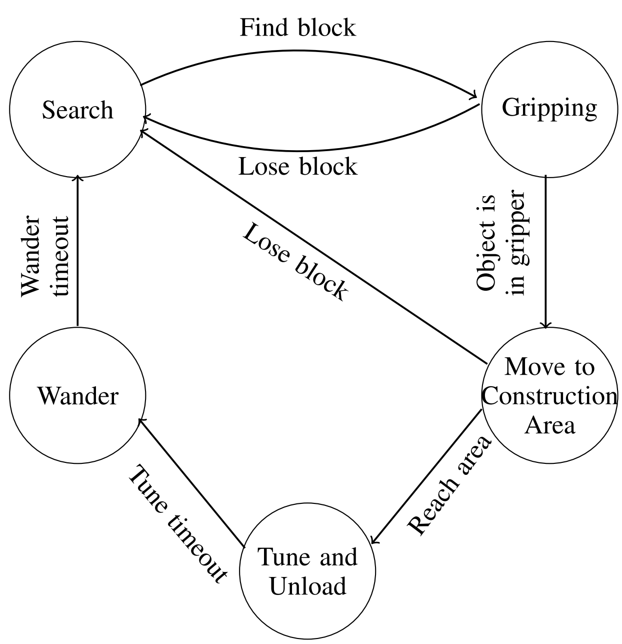


Figure 2. The finite state machine of the robots' construction behavior.

B. The adaptive construction behavior

General construction behavior allows for the construction of a structure (here a wall) at a desired location of the arena. However, it does not include the recognition of the construction dynamics. Therefore, we extend the general construction behavior to the adaptive construction behavior, in which robots tune their behaviors in respect to the dynamics of the construction task. The absence of building instructions and the dynamics of the construction process belong to the main challenges of a construction task. The main difficulty for the individual robots would be to recognize the degree of progress achieved at the macroscopic level. However, recognize this macroscopic feature and adopt the individual behavior accordingly to it allows the swarm to cope with the dynamics of the task and thus perform it more efficiently. Figure 3 shows the bi-directional link between the microscopic behavior of the individuals and the macroscopic performance of the swarm.

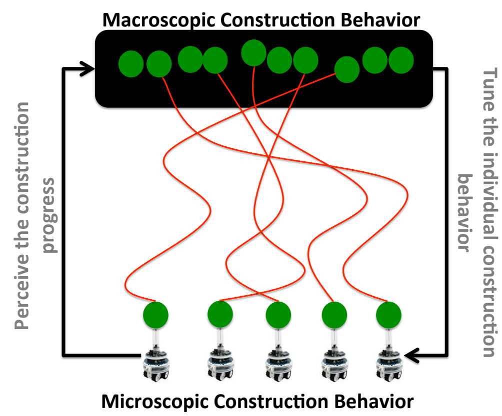


Figure 3. The micro-macro link in the construction task.

In order to recognize the dynamics of the construction task at the microscopic (individual) level, robots measure the time required to unload their building blocks at the construction area. This time is referred to as the *unload-time* – it starts from the moment the robot arrives carrying the building block to the construction area up to the moment the robot unloads the block successfully. It includs the time spent by the robot looking for a suitable location for unloading the block. While the construction of the wall proceeds, it becomes more difficult for the robots to find a free location to unload their building blocks and hence longer unload-time is experienced. Longer the time the robot spends in searching for a suitable location to unload, higher the probability is of having the progress of the construction at an advanced stage. Consequently, less blocks need to be transported to the construction area and less robots are required for continuing the task. Based on that, in the adaptive construction behavior robots can be in one of the following states: the *constructing* state or the *resting* state. At the constructing state the robot participates in the building activities captured in Figure 2. Whereas, the resting state is selected when the robot decides to leave the construction task for the moment. The switch between these two states is performed probabilistically. The probability to switch from the constructing state to the resting state is denoted by $Prob_r$ and the probability of switching from the resting state to the constructing state is denoted by $Prob_c$.

$$Prob_c = 1 - Prob_r$$

During the task execution, a robot which is at the constructing state switches to the resting state with the probability $Prob_r$ or stays in the constructing state with the probability $Prob_c$. Similarly, a robot at the resting state switches to the constructing state with the probability $Prob_c$ or stays at the resting state with the probability $Prob_r$. Figure 4 illustrates the two states and the different switching probabilities.

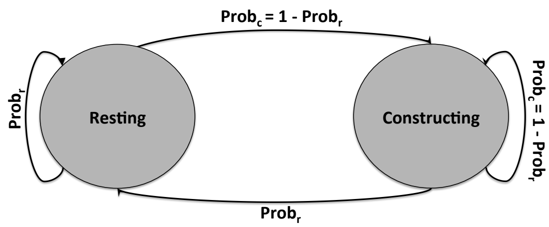


Figure 4. Robot's states under the adaptive construction behavior.

Let us observe the particular transport of the i-th building block by a robot. We use Δt_i to denote the time required to unload the i-th block. This is the unload-time of the i-th block and it is measured independently by the robot itself. The unload-time of the previous block is denoted by Δt_{i-1}. If the robot has the following condition true:

$$\Delta t_i >= \Delta t_{i-1} + \alpha$$

where α is a design parameter, it means that the latest unload-time was longer than the previous unload-time with the period α. Thus, the robot starts to contact its local neighbors in order to inform them that the unload action is getting more difficult. This indicates a specific progress in the construction process. Therefore, less blocks maybe required and consequently less robots need to participate on the building task. Each robot that receives the message increases its resting probability $Prob_r$ as follows:

$$Prob_r = min\{Prob_r + \Theta_r, 1\}$$

where Θ_r is the probability increment step and it represents a design parameter.
However, when the robot perceives a shorter unload-time than the previous one meeting the following condition:

$$\Delta t_i < \Delta t_{i-1} + \alpha$$

It is interpreted at the individual level as having an easier unload action than the previous one. This can be the result of having the construction task at an early stage, or having a gap in the constructed wall that needs to be filled with blocks. It can be also an indication of a new section in the arena that needs to be isolated by constructing a new wall. Whatever the reason is, the robot starts to broadcast this information to its local neighbors announcing the increasing need to participate on the construction activities. This message decreases the resting probability ($Prob_r$) and increases the constructing probability accordingly, as in the following:

$$Prob_r = max\{Prob_r - \Theta_c, 0\}$$

where Θ_c is the probability increment step and it represents a design parameter. In this paper, we assume to have $\Theta_c = \Theta_r$ The adaptive construction behavior can result in the following improvements:

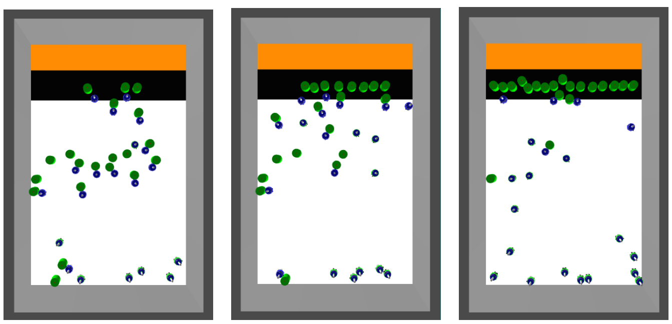
- Recognizing the dynamics of the macroscopic construction performance and acting accordingly.
- Providing a resource-efficient solution: by using the necessary amount of building blocks and preserve the rest for other construction tasks.
- Providing a robot-efficient solution: by using the number of robots required currently. This leads to preserve robots for joining new construction tasks.

Robots that apply the adaptive construction behavior exploit both indirect communication (stigmergy) and local communications with their direct neighbors. Stigmergy can be observed in the interpretation of the length of the unload-time by the individual robots. This time is directly related to actions taken by other robots, namely, to previous unload actions. Hence, it represents a piece of information transferred using the physical environment. Direct communication is used, on the other hand, to inform the local neighbors about the difficulty of the unload action in order to enable them to take an appropriate decision concerning their next state.

V. Experiments and Discussion

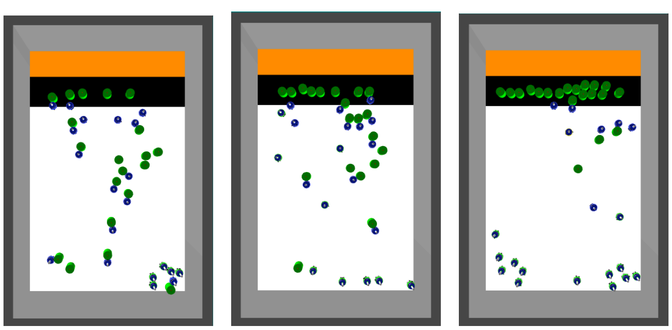
In this section, we present a set of physics-based simulations in order to verify our approaches performed using the state-of-the-art simulator ARGoS [15]. ARGoS is an efficient simulator that allows to simulate large swarms of robots with taking the desired level of physical details into consideration. In our swarm, we are using foot-bots – wheeled robots equipped with proximity sensors, cameras, a gripper, and a range and bearing system. We consider a $6 \times 4\ m^2$ working arena that is divided in three parts: a $0.8 \times 4\ m^2$ undesired part (a dangerous section) which is depict in orange at the top of the arena, a $4.5 \times 4\ m^2$ safe section that is depicted in white, and the $0.7 \times 4\ m^2$ construction area. The construction area is indicated by a black strip on the floor in addition to a set of lights that helps navigating the robots at the working arena. The robot navigation is performed as a combination between random walks and attraction and repulsion to the lights deployed in the environment. In real-world scenarios, the construction area could be indicated with other environmental parameters such as light density, humidity, or others. We are using cylinder building blocks, each with a diameter of $0.2\ m$, thus 20 building blocks are enough to construct the desired wall. Initially, both robots and building blocks are scattered uniformly at the safe section of the arena and the positions are chosen at random for each new experiment. We set the running time of each experiment to 3000 seconds. Furthermore, two configurations of the construction experiments are used, one with 20 building blocks and the other is with 60 building blocks.

As mentioned above, 20 building blocks is the amount sufficient to build the desired wall based on the dimensions of the constructions area. We first allow the robots to use the general construction behavior and afterwards the adaptive construction behavior. A set of snapshots at different time steps during a particular trail of the construction process are depicted in Figure 5 and in Figure 6. As we can notice, both behaviors perform well in constructing the wall according to the required criteria. However, the remarkable difference in the performance between the general and the adaptive behavior can be seen in the experiments in which 60 building blocks are used. Figure 7 shows the progress of the construction when robots are using the general construction behavior. As we can see, robots in this case are not able to recognize the progress of the construction process over time. Thus, they are not reacting in an adaptive manner to the dynamics of the construction task. Therefore, they continue to use building blocks as long as they are available or up to the end of the experiment (i.e., second 3000). This leads to the thick structure we can observe in Figure 7c. On the contrary, when robots use the adaptive construction behavior, they become able to recognize and adapt to the dynamics of the construction task. This is what we can observe clearly in Figure 8, in which robots stop to participate on the construction task over time affected by the feedback given by other robots about the increasing difficulty of unloading a building block. The improvement in the quality of the obtained wall is clear in Figure 8c. Moreover, Figure 8 depicts no increment in the mass of the wall after the time step 2000. This means that robots applying the adaptive construction behavior become much earlier available to join other tasks than robots applying the general construction behavior, thanks to the ability of recognizing the end of a construction task.



(a) At t.s. 300 (b) At t.s. 500 (c) At t.s. 1000

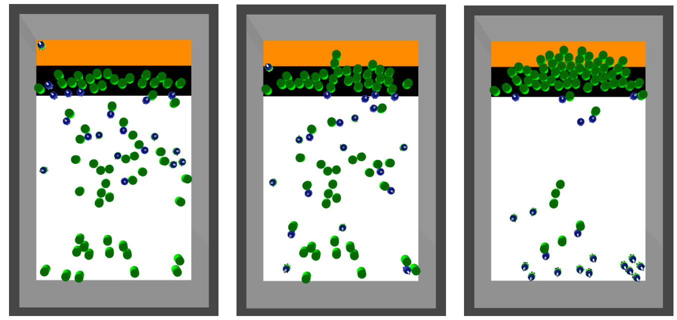
Figure 5. Snapshots of the wall construction task using 20 blocks at different time steps. Robots are applying the general construction behavior.



(a) At t.s. 300 (b) At t.s. 500 (c) At t.s. 1000

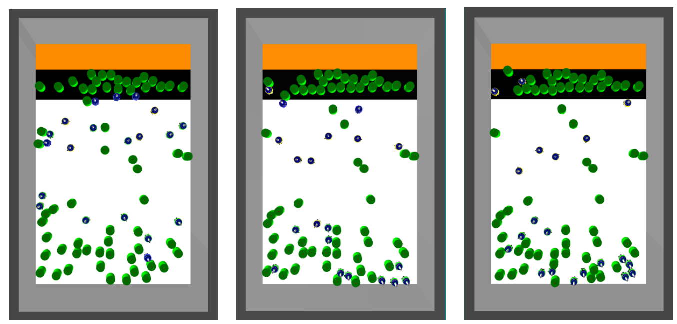
Figure 6. Snapshots of the wall construction task using 20 blocks at different time steps. Robots are applying the adaptive construction behavior.

We have repeated each of the 4 experiments, presented above, 30 times and the quality measures of the obtained walls in addition of the number of used blocks were averaged. Figure 9 shows the number of building blocks used in constructing the desired wall (We depict both the mean and the standard deviation). In Figure 9a, the available amount of blocks is 20 and we can observe that the amounts used by both the general and the adaptive behavior are similar. Whereas, the amount



(a) At t.s. 1000 (b) At t.s. 2000 (c) At t.s. 3000

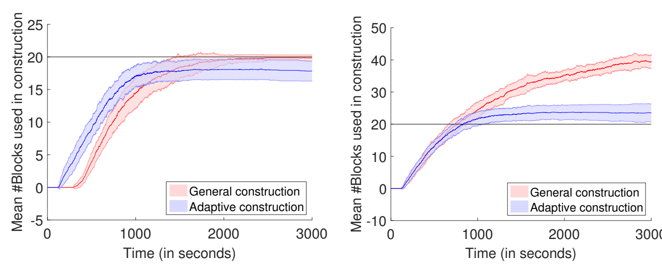
Figure 7. Snapshots of the wall construction task using 60 blocks at different time steps. Robots are applying the general construction behavior.



(a) At t.s. 1000 (b) At t.s. 2000 (c) At t.s. 3000

Figure 8. Snapshots of the wall construction task using 60 blocks at different time steps. Robots are applying the adaptive construction behavior.

used by the general behavior diverges significantly from the one used by the adaptive behavior when 60 blocks are used. This what we can see in Figure 9b, in which the amount of blocks used by the adaptive behavior stays near the sufficient amount.



(a) 20 building blocks. (b) 60 building blocks.

Figure 9. The number of building blocks used by both the general and the adaptive construction behaviors. (a) when 20 blocks are used, (b) when 60 blocks are used.

The quality metrics of the wall were averaged over 30 runs of the different experiments and as we can see in Figure 10, Figure 11, and Figure 12 both behaviors: the general and the adaptive have achieved walls with a high quality and with near-to-optimal thinness, compactness and coverage.

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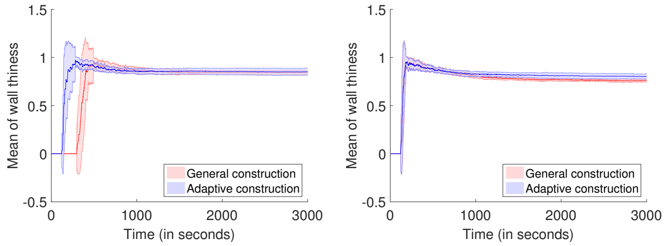
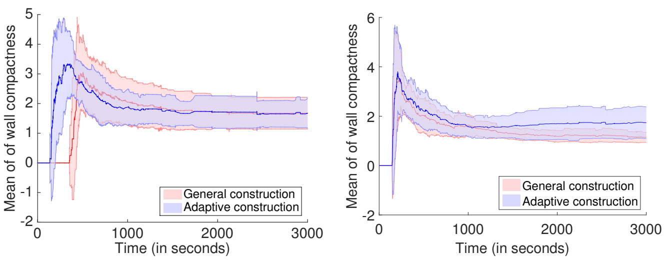


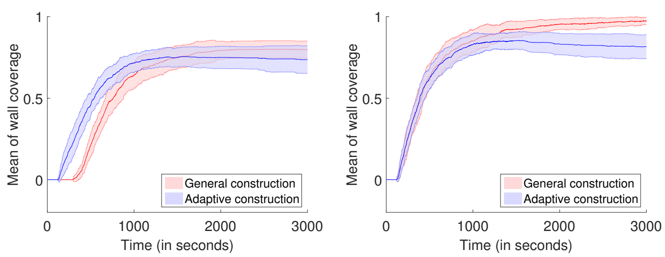
(a) 20 building blocks. (b) 60 building blocks.

Figure 10. The wall thinness achieved by both the general and the adaptive construction behaviors. (a) when 20 blocks are used, (b) when 60 blocks are used.



(a) 20 building blocks. (b) 60 building blocks.

Figure 11. The wall compactness achieved by both the general and the adaptive construction behaviors. (a) when 20 blocks are used, (b) when 60 blocks are used.



(a) 20 building blocks. (b) 60 building blocks.

Figure 12. The wall coverage achieved by both the general and the adaptive construction behaviors. (a) when 20 blocks are used, (b) when 60 blocks are used.

VI. Conclusion

The self-organized construction behavior is a main part of a wide range of tasks at which swarm robotics are planned to be deployed in the future. Therefore, it represents an attractive research challenge, specifically when no building instructions are known a priori or coded in the system. In this paper, we first define a set of quality criteria of the desired wall. Afterwards, we propose two construction behaviors that can be applied by a swarm of simple and homogenous robots. The first is the general construction behavior, which includes a set of simple rules that allow the robots to wander in an unknown arena, search for building blocks, grip them and navigate to where they should be placed. One of the main challenges, here, is to unload the building block properly such that the emergent wall respects the given quality metrics. The general behavior performs optimal, when only the sufficient amount of building blocks is available or when the time of the construction task is set to be the required one. The adaptive construction behavior, on the other hand, is designed using a probabilistic approach to cope with the dynamics of the construction task. It allows the robots to recognize the progress of the construction task over time and to act accordingly. The adaptive construction behavior achieves high quality walls similar to the general construction behavior. However, it both avoids the use of unnecessary building blocks and sets the robots earlier free for participating on other tasks through realizing the end of the current construction task.

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