A Mechanism to Self-Assemble Patterns with Autonomous Robots

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Abstract. There are examples of robotic systems in which autonomous mobile robots self-assemble into larger connected entities. However, existing systems display little or no autonomous control over the shape of the connected entity thus formed. We describe a novel distributed mechanism that allows autonomous mobile robots to self-assemble into pre-specified patterns. Global patterns are 'grown' using locally applicable rules and local visual perception only. In this study, we focus on the low-level navigation and directional self-assembly part of the pattern formation process. We analyse the precision of this mechanism on real robots.

1 Introduction

Much research has been devoted to the capabilities of distributed swarms of cooperating, autonomous robots [1]. In some of these systems, multiple robots can *self-assemble* into larger structures in order to overcome the physical limitations of the individual agents. For example, multiple connected robots can transport objects too heavy to be moved by an individual robot [2], or navigate terrain impassable by a robot navigating alone [3].

Existing self-assembling systems, however, have very little autonomous control over the shape of the connected structures they form. In this paper, we present the low-level control aspects of a distributed control mechanism that allows autonomous mobile robots to self-assemble into specific, connected patterns. Three examples of patterns are shown in Fig. 1. Patterns are 'grown' using local visual perception only. Robots that are already attached to the pattern indicate where new robots should attach in order to grow the local structure appropriately. For a detailed study of the high-level control principles and the group-level performance of the proposed mechanism, see [4].

2 Related Work

Related research areas include self-reconfigurable robotics and formation control. Self-reconfigurable robotic systems are made up of modular robots that

Fig. 1: Examples of whole patterns: Rectangle, star, and line.

can connect to each other in different ways so as to autonomously change their global morphology. Examples of such systems include Yim *et al.*'s PolyBot [5, 6], Hirose *et al.*'s Gunryu [7], and Fukuda *et al.*'s CEBOT system [8, 9]. PolyBot is a modular chain robot in which each module has one degree of freedom. It has been demonstrated that an arm consisting of multiple PolyBot modules is capable of operating in 3D space and that such an arm can grasp and dock with additional modules. In the Gunryu system, each robot is capable of autonomous locomotion and equipped with an actuator that allows robots to form physical connections with each other. CEBOT is a system consisting of heterogeneous modules with different functions, e.g. to rotate, move, and bend. Various prototypes of the CEBOT system comprising different shapes and connection mechanisms have been studied. However, these systems tend to be limited either in their ability to configure themselves autonomously or in their ability to self-assemble. Castano *et al.* has proposed a system of homogeneous modules called CONRO [10]. Rubenstein *et al.* have recently been shown that CONRO is capable of autonomous docking (self-assembly) [11].

In formation control research, groups of robots are steered into one or more pre-specified formations. Mechanisms to maintain these formations while the group is in motion are also studied. Proposed approaches include the use of *virtual structures* [12, 13], leader-follower schemes [14, 15], and decentralised, behaviour-based methods [16–18].

Most existing approaches rely either on global communication or on each robot having access to a blueprint of the global pattern (or both). Much of the research has been conducted in simulation only. In the study presented in this paper we use real robots to self-assemble global patterns using a completely distributed algorithm. None of the robots has access to a blueprint of the global pattern. The algorithmic rules are based on local information only. None of the robots except the *seed* robot has any predefined position in the pattern.

3 Hardware Platform

We use a number of real robots known as *s-bots* [19]. The *s-bot* platform has been used for several studies in swarm intelligence and collective robotics. Overcoming

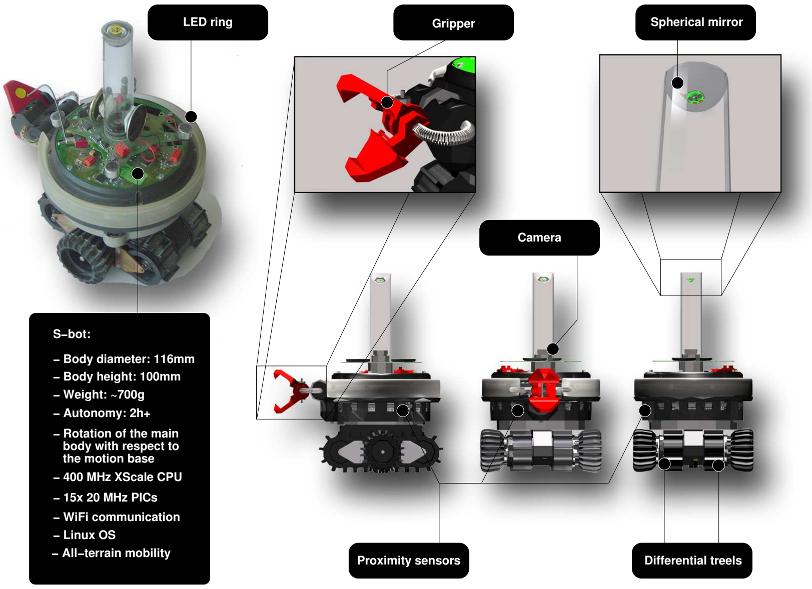

Fig. 2: *s-bot*: An autonomous, mobile robot capable of self-assembly.

steep hills and transport of heavy objects are notable examples of tasks which a single *s-bot* could not solve individually, but which have been solved successfully by teams of self-assembling *s-bots* [2, 20, 3].

Each *s-bot* is equipped with an Xscale CPU running at 400 MHz, a number of sensors including an omni-directional camera, light and proximity sensors. Each *s-bot* also has a number of actuators. These include 8 sets of RGB coloured LEDs distributed around the circumference of the *s-bot* body. These LEDs can be controlled individually and can be perceived by other robots at a range of up to approximately 50 cm depending on light conditions. The *s-bots* also have a gripper that allows them to form physical connections with one another. The sensors and actuators are indicated in Fig. 2.

4 Growing Global Patterns

In this study, we consider patterns formed by groups of self-assembling robots. We start from a single predesignated robot, the *seed*, that indicates where other robots can attach to it. In principle, the seed could be chosen probabilistically [3] or it could be the first robot that encounters a situation that requires self-assembly into a given morphology. Since we focus on pattern formation in this study, we pre-configure one *s-bot* to be the seed. At the beginning of each experiment the robots are instructed which pattern they should form (e.g., arrow, star

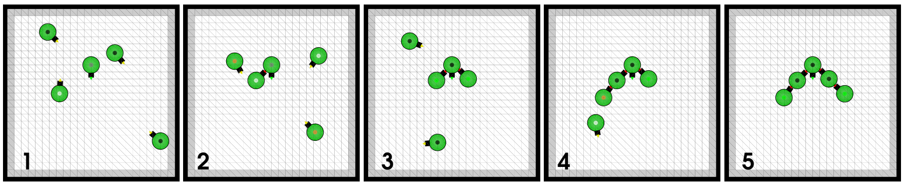

Fig. 3: Example of an arrow pattern being formed by a group of 5 *s-bots*.

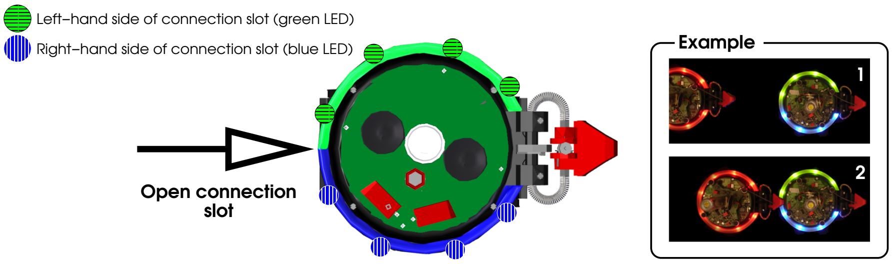

Fig. 4: An example of a *s-bot* with an open connection slot to its rear. The *s-bot* has lit up its left green LEDs and its right blue LEDs. Right: An example with real robots.

or line). As new robots attach to the connected structure, they indicate where other non-attached robots should attach in order to extend the structure appropriately. However, none of the robots have any knowledge about the global state or shape of the connected structure at any time. None of the robots (except the seed in this study) has a predefined location in the final pattern. An example of the formation of an arrow pattern is shown in Fig. 3.

5 Low-level Pattern Formation Mechanism

5.1 Overview

The robots coordinate using their camera and coloured LED ring. Our control mechanism makes use of the colours red, green and blue. Green and blue indicate the left-hand side and right-hand side of a *connection slot*, respectively. A connection slot specifies a location and a direction in which the pattern should be extended. An example is shown in Fig. 4. An *s-bot* can open connection slots in 7 different locations and directions (each robot has 8 sets of LEDs and a slot can be opened between any two neighbouring LEDs, except between the two front LEDs where the gripper is mounted). Non-attached robots light up their red LEDs in order to be visible to other robots.

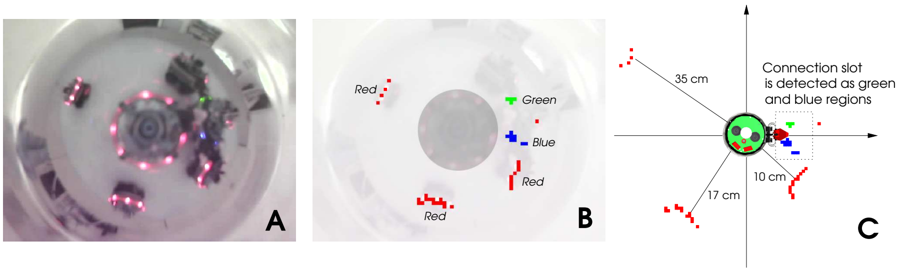

Fig. 5: An image captured by a robot's omni-directional camera and the processing steps to obtain the relevant information about the surroundings. A: The captured image. B: After colour segmentation. C: The extracted information about the position of the other robots and the connection slot.

5.2 Sensory Information

The camera sensor captures 640x480 colour images. The *s-bots* have sufficient on-board processing power to scan the entire image and identify objects based on colour information. The image processor is configured to detect the location of the coloured LEDs of the *s-bots* and discard any other information. The image processor divides the image into a grid of multi-pixel blocks and returns the segmented colour prevalent in each block (or indicates the absence of any segmented colour). The *s-bot* camera captures images of the robot's surroundings reflected in a semi-spherical mirror. Since the *s-bots* operate on flat terrain, this means that the distance in pixels from the centre of an image to a perceived object corresponds to the physical distance between the robot and the object. An example is shown in Fig. 5.

The cameras have a range of approximately 50 cm. Like most sensors on mobile robots, the readings from the camera are subject to a significant amount of noise. Objects are not always perceived even when they are in range of the camera, and due to occlusions one robot cannot see all the LEDs on another robot unless the two robots are adjacent. Furthermore, as a robot moves, objects tend to "jump around" from frame to frame due to the shaking of the perspex tube holding the camera and the spherical mirror (a difference of a few pixels can have a considerable impact on the computed location relative to the perceiving robot). Despite the sensory limitations of individual *s-bots*, we do not have to resort to using global communication or a global pattern blueprint. We generate consistent global patterns by leveraging distributed control principles — each robot acts solely on the basis of what it perceives in its immediate vicinity.

5.3 Navigation to a Connection Slot

Non-attached *s-bots* (i.e., *s-bots* that have not yet attached to the pattern) start by searching for an open connection slot. An open connection slot can be on either the *seed* robot or on other robots that have already attached to the pattern. If a non-attached *s-bot* cannot see any coloured LEDs, it performs a random walk until it perceives one or more LEDs. If a non-attached *s-bot* can see an open connection slot (i.e., blue or green LEDs), the *s-bot* tries to navigate around the connected structure until it has the correct position and alignment to attach to the slot.

The different navigation zones around an *s-bot* with an open connection slot to its rear are shown in Fig. 6. A non-attached *s-bot* takes different actions according to the zone in which it is located. If an *s-bot* is more than 30 cm away from the connection slot, it navigates directly towards the slot. If an *s-bot* is within 30 cm of the slot and it is in the *go around zone*, the *s-bot* attempts to navigate around the connected structure, randomly choosing either the clockwise or the counter-clockwise direction. Once inside the *inner grip zone* the *s-bot* first navigates to the *intermediate spot* before approaching the connection slot. This two-phase strategy enables the non-attached *s-bot* to approach the connection slot with the correct alignment. If, during the approach, the *s-bot* exits the *outer grip zone*, it switches back to navigating around the connected structure.

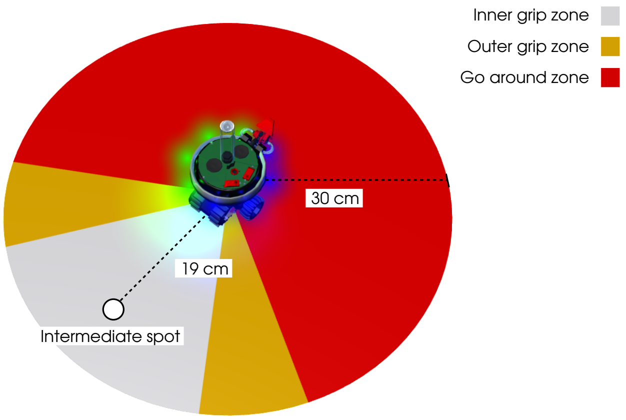

Fig. 6: The *intermediate spot* and navigation zones around an *s-bot* that has opened a connection slot to its rear.

5.4 Forming a Directional Connection

Once an *s-bot* is in the *inner grip zone*, the challenge is to steer the *s-bot* to the connection slot so that the position and orientation are correct when it attempts to grip. This procedure takes place in three steps: 1) Go to the *intermediate spot*, 2) Turn to face the connection slot, and 3) Navigate to the connection slot and connect.

The closer a robot gets to a connection slot, the more accurately it perceives the location and the direction indicated. Corrections to the trajectory are made continuously as the robot approaches the slot and as more accurate positional information becomes available. The *intermediate spot* is calculated by the non-attached *s-bot* to be 19 cm away from the *s-bot* with the open connection slot in the direction indicated by the slot (see Fig. 6). This means that the robot has a course of approximately 13 cm (19 cm minus the radius on an *s-bot*) to align itself correctly. As the robot moves closer, the speeds of the left and the right treels respectively, are set to:

$$s_l = 5.6\,\mathrm{mm/s} + 21.8\,\mathrm{mm/s} \cdot \frac{d}{130\,\mathrm{mm}} \cdot f(\theta), \tag{1}$$

$$s_r = 5.6\,\mathrm{mm/s} + 21.8\,\mathrm{mm/s} \cdot \frac{d}{130\,\mathrm{mm}} \cdot f(-\theta), \tag{2}$$

where d is the distance to the connection slot, and $f : \theta \to [0, 1]$ is a function that maps the angular difference between the current heading and the ideal heading, θ, to a speed modifier in the range $[0, 1]$. The result of applying this speed modifier term to Eqn. (1) and Eqn. (2) is that the *s-bot* continually corrects its alignment as it approaches the connection slot. During the approach, the speed of the treels is reduced as a linear function of the distance to the connection slot (the magnitude of the alignment corrections becomes correspondingly smaller). When the robot determines that it is close enough to connect, it attempts to grip. If the *s-bot* detects that the grip was successful, it assumes that it is now part of the connected pattern. If, on the other hand, the grip fails, the robot moves back and starts navigating to the *intermediate spot* again.

Pattern growth is determined by three sets of pattern extension rules: one set of rules for the *seed* robot, one set for robots already in the pattern that have just received a connection, and one for robots that have just connected to the pattern. By manipulating these three sets of rules, we are able to form different patterns [4].

6 Results

We analysed the precision of the directional self-assembly mechanism that allows an attached robot to specify the position and orientation with which a non-attached robot should attach to it. We conducted 96 trials in which a single non-attached *s-bot* attached to a stationary *seed* robot (12 starting positions, 8 starting orientations). The twelve starting positions were evenly distributed around a circle of radius 35 cm centred on the *seed* robot. We used a *seed* robot with a single connection slot open to its rear.

We initially considered angular precision: how accurately the connecting non-attached robot matched its alignment to the desired alignment indicated by the *seed* robot. The angular precision results are shown in Fig. 7 (top-left). Note that the mean angular misalignment is very close to zero.

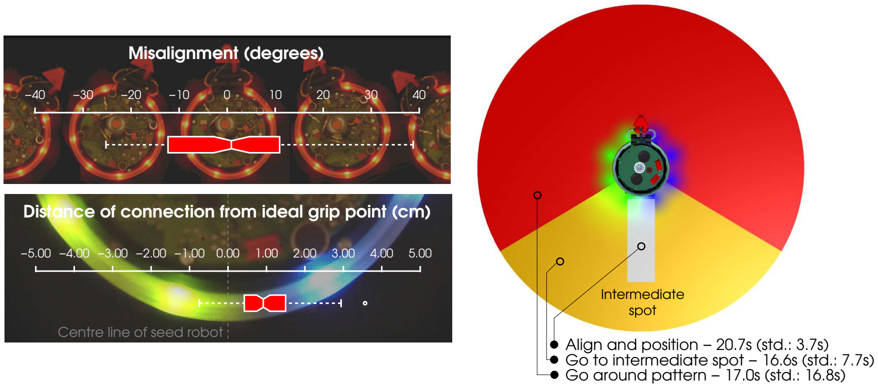

Fig. 7: Timing and precision of the pattern formation mechanism. Top-left: Angular precision. Bottom-left: Positional precision. Right: Mean time and standard deviation spent on different activities while forming a connection.

We also analysed the positional precision: how close to the ideal grip point the non-attached robot connected to the *seed*. With a connection slot to its rear, the ideal grip point is the middle of the rear of the *seed* — the point on the *seed*'s LED ring that falls on the *seed*'s centre line (in line with the *seed*'s camera and gripper). Note that it is possible for a robot to grip at the wrong point even if its alignment is perfect. The positional precision results are presented in Fig. 7 (bottom-left). There is a clear bias towards attaching to the right of the ideal grip point. This bias arises because the LEDs are not distributed in a perfectly uniform manner around the *s-bot* body. When the *seed* lights up its 4 left green LEDs, and its 4 right blue LEDs, the point to its rear equidistant between the green and blue LEDs is in fact about 1 cm to the right of its centre line. This can be seen by looking at the *s-bot* LED ring in the background of Fig. 7 (bottom-left).

The mean times spent on the different activities are shown in Fig. 7 (right). The largest share of the time was spent on positioning and alignment, that is, approaching the connection slot from the *intermediate spot*. Although the distances covered during the different activities vary significantly, the mean times spent on the different activities are comparable. This is a consequence of the increasing precision required as the *s-bot* gets closer to the connection slot — the more precision required, the slower the *s-bot* moves. The mean time from the start of a trial until the *s-bot* attached was 54.3 s.

In all 96 trials the free robot attached to the *seed* robot. In 2 of the 96 trials the free robot failed to attach on the first attempt and retreated to try another angle. In a further four of the 96 trials the non-attached robot abandoned its approach to the connection slot before attempting to grip and retreated to try another angle, as it determined that it was approaching from an incorrect angle. In one of the 96 trials the non-attached robot lost sight of the connection slot and was manually replaced on its starting position.

7 Conclusion

We have presented a low-level mechanism that enables autonomous mobile robots to self-assemble into global patterns. The mechanism relies on coloured LEDs and local visual communication. We evaluated the precision of this mechanism on real robots, and found that it allows *s-bots* to form connections at a specific point and with a specific alignment with a relatively small margin of error.

We have evaluated the mechanism in experiments where groups of real robots formed larger patterns (see Fig. 1). The performance of the entire pattern formation process is presented in [4]. Supplementary information, photos and videos can be found in [21].

An interesting direction for future research is to allow groups of robots to autonomously choose which patterns to self-assemble into, based on the nature of the obstacles encountered. In an all-terrain navigation task, for example, the group could self-assemble into a line formation in order to cross a ditch, while uneven or hilly terrain could trigger self-assembly into a dense structure that provides stability.

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