Morphology Control in a Multirobot System

Distributed Growth of Specific Structures Using Directional Self-Assembly

BY ANDERS LYHNE CHRISTENSEN,
REHAN O'GRADY, AND MARCO DORIGO

For any robotic entity to complete a task efficiently, its morphology must be appropriate to the task. If the task is well-defined in advance, the morphology of a robotic entity can be prespecified accordingly. If, however, some of the task parameters are not known in advance or if the same robotic system is required to solve several different tasks, morphological flexibility may be required. It is easy to imagine, for example, that navigating on uneven terrain and hole-crossing are likely to require different morphologies (see Figure 1).

The field of modular self-reconfigurable robotic systems is dedicated to the study of systems with morphological flexibility (for a good overview see [18]). The components of such systems can autonomously reorganize into different configurations. However, in the majority of current implementations, the components are manually preassembled, and once assembled, they are incapable of autonomously assimilating additional modules.

Self-propelled, self-assembling robotic systems, in contrast, are made up of independent autonomous mobile components that are capable of forming physical connections with each other without external direction. Such self-assembling systems are potentially more flexible than preconnected self-reconfigurable systems. To date, however, the ability of self-propelled, self-assembling systems to control their own connected morphologies remains very limited.

In this article, we propose a distributed control mechanism for a self-propelled, self-assembling robotic system that allows robots to form specific, connected morphologies. Global morphologies are grown using only local visual perception. Robots that are part of the connected entity indicate where new robots should attach to grow the local structure appropriately. We demonstrate the efficacy of the mechanism by letting groups of seven real robots self-assemble into four different morphologies: line, star, arrow, and rectangle.

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Toward Robotic System Autonomy

Related Work

Self-reconfigurable robotic systems have the potential advantages of versatility due to morphological reconfiguration, robustness due to component interchangeability, and low cost due to mass production of units. Several different hardware architectures (lattice, chain/tree, mobile) and many different implementations and control mechanisms have been proposed [3], [9], [13], [17]. In most existing self-reconfigurable robotic systems, modules are either preconnected manually or rely on their environment (be it natural or manmade) to provide the energy required for independent movement.

In self-propelled, self-assembling robotic systems, independent mobile robots autonomously form physical connections with each other, thereby forming larger robotic entities on the fly. Such systems have the same potential advantages as self-reconfigurable systems. In addition, self-propelled, self-assembling systems have the potential to act in parallel; single modules are capable of acting alone but can overcome their individual physical limitations by teaming up when necessary. Several architectures have been proposed, which have been implemented with varying degrees of success [2], [4], [6]–[8]. None of the existing systems display any meaningful control over the morphology of the connected entity formed through the self-assembly process.

The pattern growth aspect of the morphology control mechanism that we use in this study is reminiscent of techniques used in the research field of formation control [1], [5], [10], [11]. In formation control research, groups of robots steer themselves into one or more prespecified formations. Mechanisms to maintain these formations while the group is in motion are also studied. Proposed approaches include the use of virtual structures, leader-follower schemes, and decentralized, behavior-based methods. Most existing approaches rely either on global communication or on each
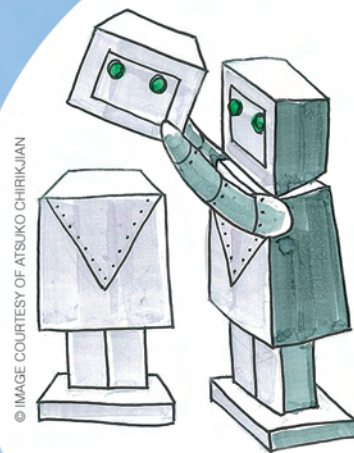
robot having access to a blueprint of the global pattern (or both). Much of the research has been conducted in simulation only.

In this article, we show for the first time how self-propelled, self-assembling robots can form specific morphologies. In contrast with many formation control mechanisms and self-reconfigurable robotic systems, our control algorithms are completely distributed; the robots in our system do not have access to a blueprint of the global pattern, and the algorithmic rules are solely based on what a single robot can see in its immediate surroundings. None of the robots have any predefined position in the final morphology, except for the seed robot that initiates the self-assembly process.

Hardware Platform

We use a number of real robots known as s-bots [12]. The s-bot platform has been used for several studies in swarm intelligence and collective robotics. Overcoming steep hills and transport of heavy objects are notable examples of tasks that a single s-bot could not solve individually but which have been solved successfully by teams of self-assembling s-bots [14]–[16].

Each s-bot is equipped with an XScale CPU running at 400 MHz and a number of sensors including an omni-directional camera, light sensors, and proximity sensors. Each s-bot also has a number of actuators. These include eight sets of individually controlled RGB colored LEDs distributed around the circumference of the main s-bot body. Using their cameras, other robots can perceive these LEDs at a range of up to 50 cm depending on light conditions. The camera records the panoramic images reflected in the spherical mirror. The images are segmented into three possible colors (red, green, blue) tuned to match the colors of the s-bot LEDs. The s-bots are equipped with a gripper that allows them to form physical connections with one another. The sensors and actuators are indicated in Figure 2.

Self-Assembly into Specific Morphologies

We use the following morphologies as case studies: line, rectangle, star, and arrow (see Figure 3).

Control Principles

Connected structures are progressively grown from a single robot, the seed. In principle, the seed could be chosen probabilistically [15], or it could be the first robot that encounters an obstacle impassable by a single robot. Since we focus on morphology control in this study, we preconfigure one s-bot to be the seed. At the beginning of each experiment, the robots are instructed which of the four morphologies they should form. However, none of the robots has a blueprint of the global connected structure. Simple rules govern the local growth of the structure. By appropriate manipulation of these rules, different global morphologies emerge. Robots that are already part of the connected structure dictate how and when other robots should assemble to them.

The robots coordinate using their camera and colored LED ring. Our control mechanism makes use of the colors red, green, and blue. Green and blue indicate the left- and
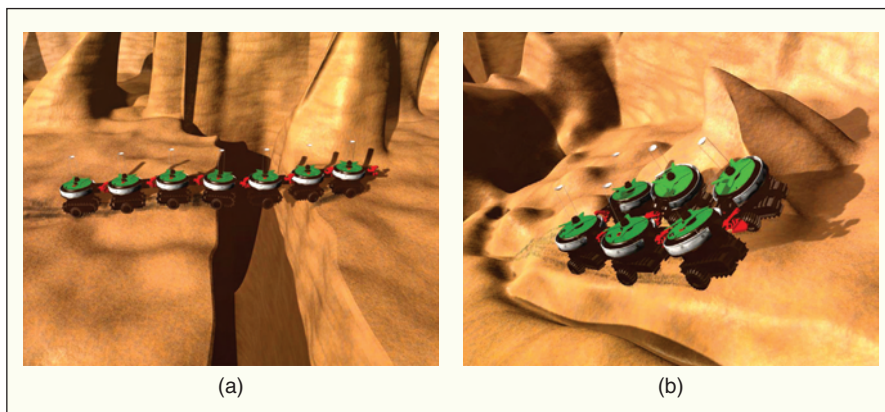
Figure 1. *Two examples of self-assembled robotic entities. (a) A connected robotic entity crosses a trough. A line formation is well-suited to this task, since it allows the entity to stretch further and requires only a minimum number of robots to be suspended over the trough at any one time. (b) A more dense structure provides greater stability for rough terrain navigation.*
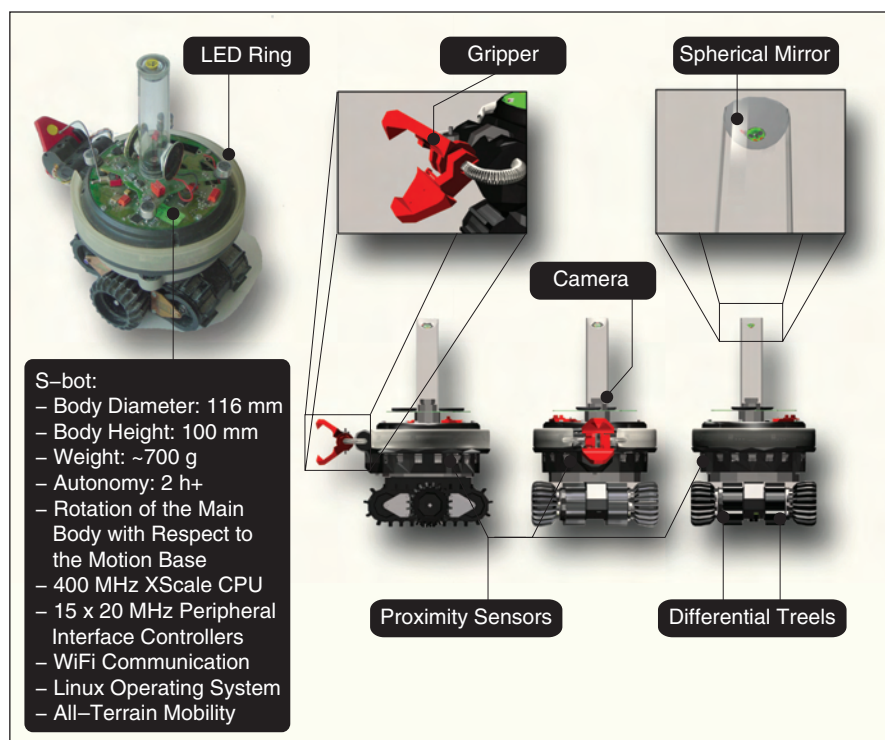
Figure 2. *S-bot: an autonomous, mobile robot capable of self-assembly.*

right-hand side of a connection slot, respectively. A connection slot specifies a location and the direction in which the current structure should be extended. An example is shown in Figure 4(a), where a robot has opened a connection slot to which another robot connects [Figure 4(b)]. The connecting robot is lit up in red. After a robot has connected, it signals that the connection slot is no longer available by briefly opening an inverse connection slot [Figure 4(c)]. We refer to this procedure as a handshake. The seed and the newly connected robot are then free to open new connection slots. In the example shown in Figure 4, the newly connected robot has opened a new connection slot to its rear [Figure 4(d)].

During the self-assembly process, all nonconnected robots (except for the seed) search for connection slots. When a robot finds a slot, it aligns itself in the direction indicated and attempts to assemble to the robot with the open slot. Once connected,

the robot can open one or more connection slots itself, according to the rules of the specific morphology being formed.

The Seed Robot

The self-assembly process is started by the seed. The seed robot opens a connection slot and waits for a free robot to connect to the slot. The behavior of the seed robot for the star morphology is shown in Figure 5. For the star morphology, the seed starts with one connection slot open and continues to open new connection slots until four robots have connected. The seed robot for the line morphology opens only one connection slot to its rear. Both the arrow and rectangle morphology seeds require two robots to connect to them. The arrow morphology seed robot starts with an open connection slot to its front left. Once a robot has connected to that connection slot, the arrow seed opens a second connection slot to its front right. The rectangle morphology seed starts with a connection slot to its rear. Once a robot has connected to that slot, the rectangle seed opens a second connection slot to its right.

The Free Robots

We refer to a robot that is not yet part of the connected structure as a free robot. The free robots search for an open connection slot and then try to connect to the slot. The logic for this part of the self-assembly process is common to all morphologies and is shown in Figure 6. If a free robot cannot see any colored LEDs, it performs a random walk until it can see some LEDs. If a free robot can see an open connection slot (i.e., either blue or green LEDs), the robot tries to navigate around the connected structure until it has the correct position and alignment to attach to the connection slot. While it is performing this navigation, it turns on its red LEDs.

If a free robot can only see red LEDs (and cannot therefore see a connection
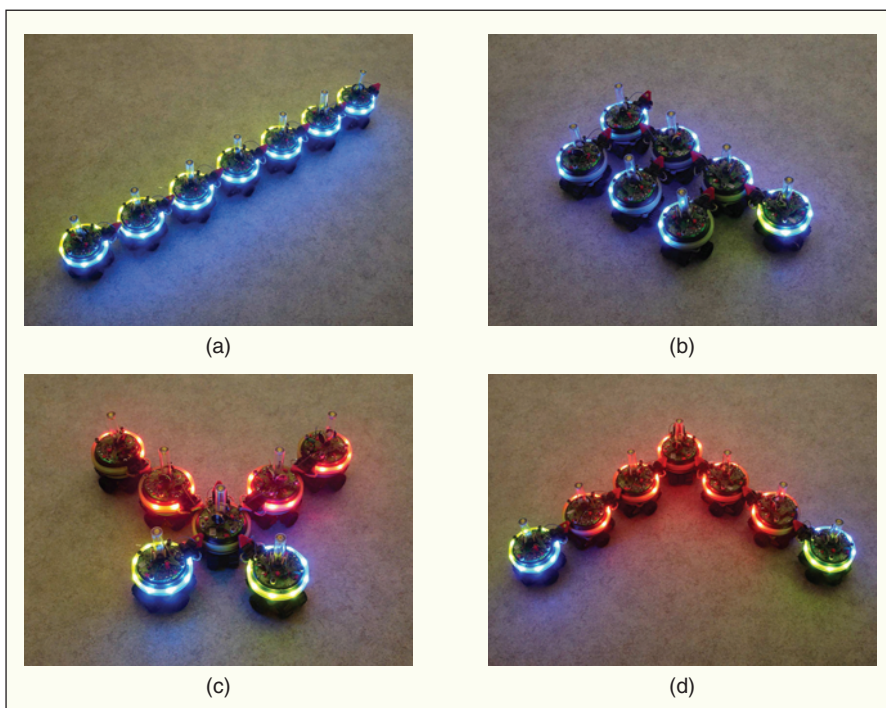
Figure 3. *Four different morphologies constructed with seven real robots: (a) line, (b) rectangle, (c) star, and (d) arrow. (The rectangle and star morphologies would become balanced with the addition of more robots.)*
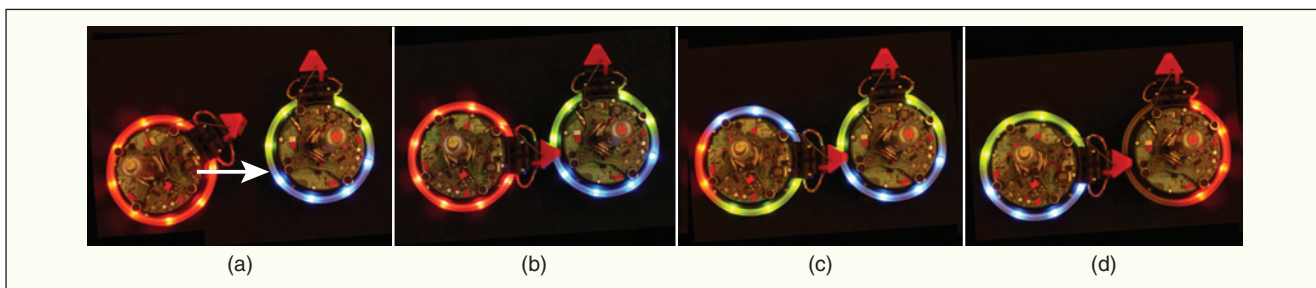
Figure 4. *The communication and coordination mechanism for morphology growth is based on colored LEDs and vision. The colors green and blue indicate the left-hand side and the right-hand side of a connection slot, respectively. (a) A white arrow indicates the position of the connection slot and the correct alignment of a robot connecting to the slot. (b) The robot connects. (c) The robot then performs a handshake to signal that it has filled the connection slot. (d) Afterwards, the newly connected robot opens a new connection slot to its rear to grow the structure further.*

slot), it switches off its own LEDs and navigates toward the closest red LED. The assumption is that this red LED must belong to a robot within visual range of a connection slot. This mechanism helps to compensate for the relatively short perception range of the s-bots (approximately 50 cm). (During initial experiments before this logic was implemented, free robots would often spend a significant amount of time at the edges of the arena searching for the connected structure.)

Once the free robot has the correct alignment and position relative to the connection slot, it approaches the connection slot and attempts to connect. If the free robot sees red LEDs between itself and the connection slot during this approach phase, the robot assumes that there is another free robot already trying to connect to that slot. Therefore, it abandons its approach, moves back, and waits a random amount of time before proceeding. This is to prevent the free robots from obstructing each other by trying to connect to the same connection slot at the same time.

Connected Robots
When a free robot connects to the structure, it becomes a connected robot, and code specific to the particular morphology is executed. The control flow for the connected robots is shown in Figure 7 and described in the subsequent paragraphs.
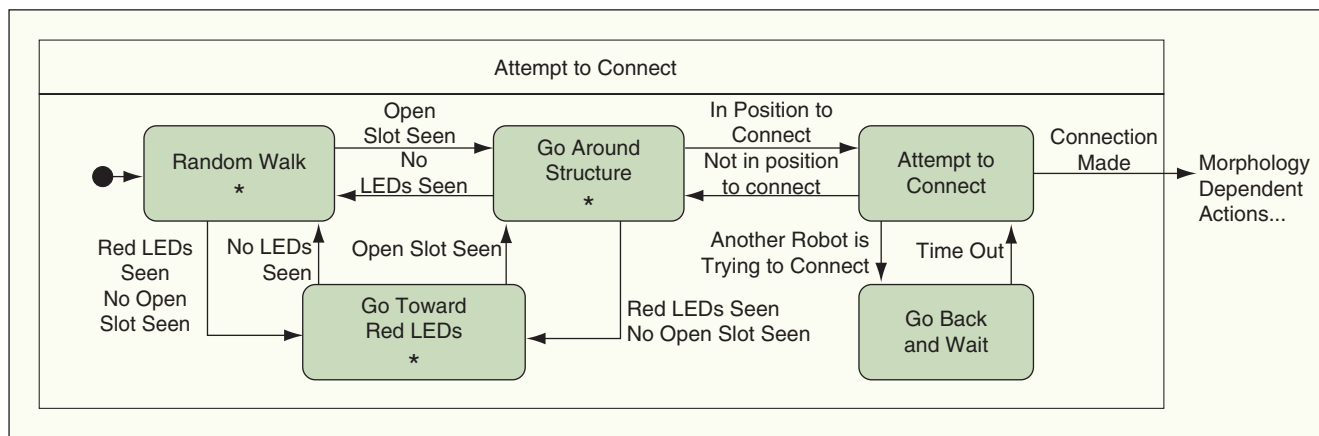
Line Morphology
When a robot connects to the structure, it opens a new connection slot to its rear. The green and blue LEDs that form this new connection slot remain lit, even after another robot has attached to it. In this way, the whole line points to the rear of the connected structure. Thus, as long as a free robot can see any part of the structure, it can navigate to the open connection slot, even if the connection slot itself is out of the robot's visual range.

Rectangle Morphology
When a robot connects to the structure, it has to determine its location in the connected structure. There are two types of location: A or B (see Figure 7). If it is in a B location, the robot has to open new connection slots to extend the connected structure. If the robot is in an A location, it should not open any connection slots. A newly connected robot determines its location in the connected structure by observing what happens during the handshake. If it sees green and blue LEDs in front of it, the robot is in
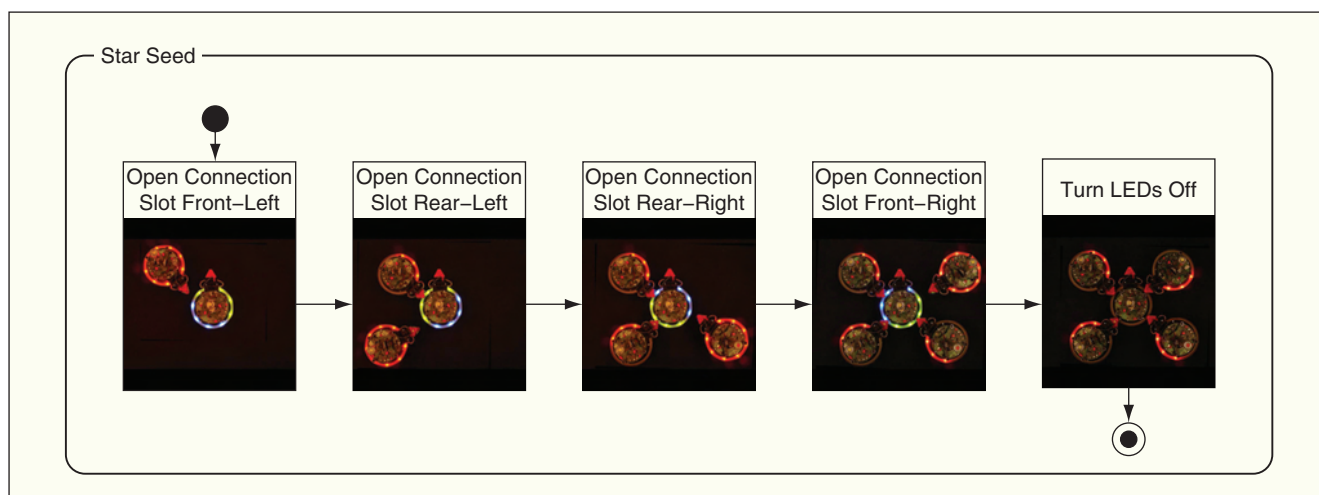
Figure 5. Behavior of the seed robot for the star morphology. The seed first opens a connection slot to the front-left and then continues to open connection slots in the counter clockwise direction until four s-bots have connected. After the last robot has connected, the seed turns off its LEDs. At any given time, the seed has only one connection slot open.

Figure 6. Morphology independent control logic for free robots. Obstacle avoidance based on vision and proximity sensor readings is performed in the three control states marked by an asterisk (*).

an A location. If it only sees blue LEDs, it is in a B location and opens new connection slots, first to its left and then to its rear.

Arrow and Star Morphologies

When a free robot connects to the structure, it does not open a connection slot immediately. Instead, it waits until it sees no open slots before opening a connection slot itself. This keeps the morphology balanced for at least as long as the whole connected structure is within visual range of each newly connected robot. During this period, the two arms of the arrow morphology differ by at most one robot in length. The same mechanism encourages the star morphology to grow in rings. At first, four robots connect to the seed, and it is only after they have all connected that the first ring opens new connection slots.

Results and Analysis

### *Directional Self-Assembly Mechanism*

We analyzed the precision of the low-level self-assembly mechanism we used to create directional connections. We conducted 96 trials in which a single free robot connected to a stationary seed robot (12 starting positions, eight starting orientations). The 12 starting positions were evenly distributed around a circle of radius 35 cm centered on the seed robot. We used a line morphology seed robot, i.e., a robot with a single connection slot open to its rear.

We initially considered angular precision: how accurately the connecting free robot matched its alignment to the desired alignment indicated by the seed robot. As we used the line morphology seed in these experiments, the connecting robot should match its alignment exactly to that of the seed robot. The angular precision results are shown in Figure 8(a). Note that the mean angular misalignment is very close to zero.

We also analyzed the positional precision: how close to the ideal grip point the free robot connected to the seed. For the line morphology seed, 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 center line (in line with the seed's camera and gripper). Note that it is possible for the free robot to grip at the wrong point even if its alignment is perfect.

The positional precision results are presented in Figure 8(b). There is a clear bias toward connecting to the right of the ideal grip point. This bias arises because the LEDs are not distributed
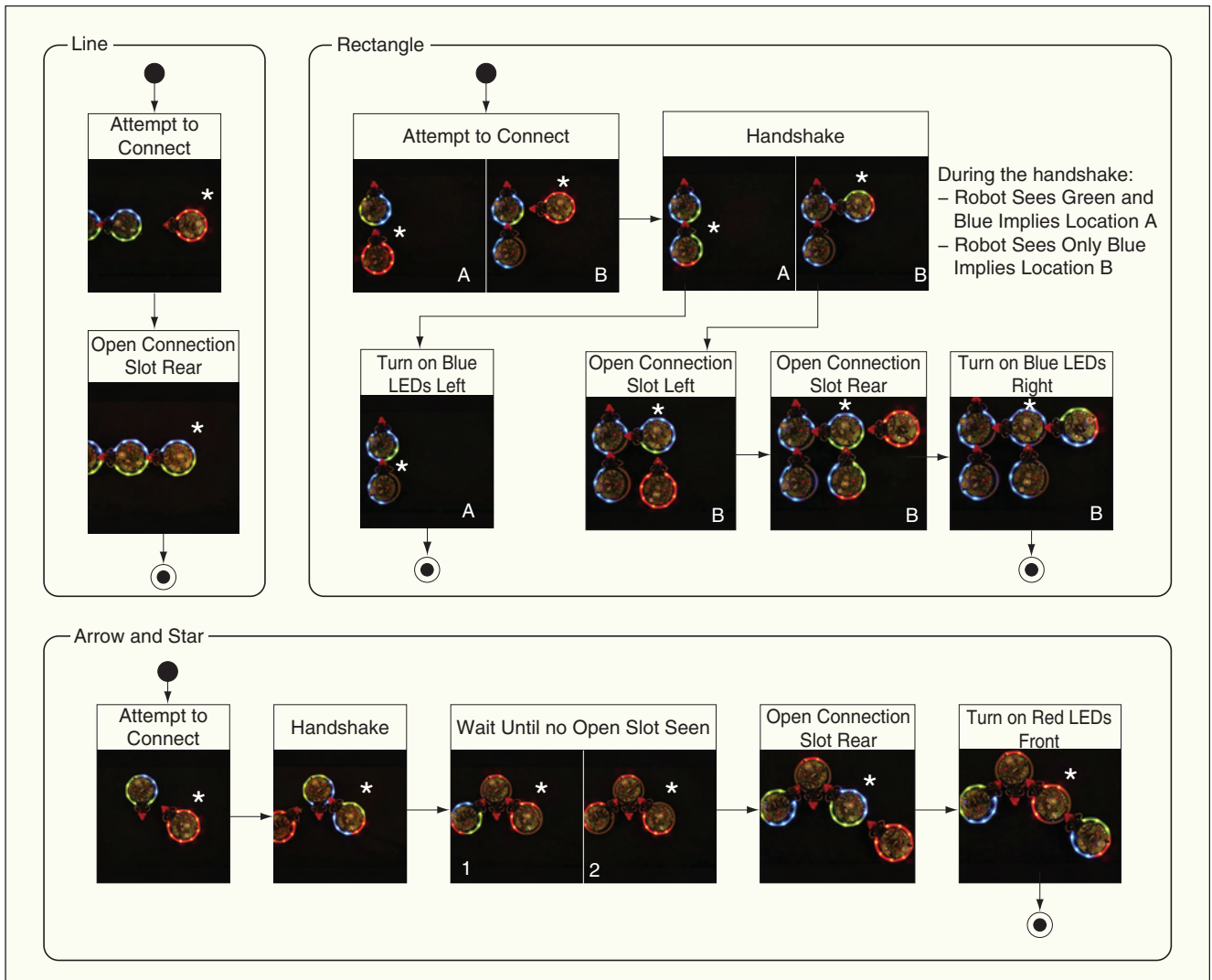
Figure 7. *Morphology dependent control logic for connected robots. For each state, the white asterisk indicates the robot being described.*

in a perfectly uniform manner around the s-bot body. When the line morphology seed lights up its four left green LEDs, and its four blue right LEDs, the point to its rear equidistant between the green and blue LEDs is in fact about 1 cm to the right of its center line. This can be seen by looking at the s-bot LED ring in the background of Figure 8(b).

In all 96 trials, the free robot connected to the seed robot. In two of the 96 trials, the free robot failed to connect on the first attempt and retreated to try another angle. In a further four of the 96 trials, the free 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 free robot lost sight of the connection slot and was manually replaced on its starting position.

Formation of Complete Structures

For each of the four different morphologies, we conducted ten trials in which we self-assembled a specific morphology using seven robots. We used a walled arena of 220×220 cm.

For all trials of a given morphology, we placed the seed in the same starting position and orientation. The starting positions of the free robots were randomly sampled without replacement from 12 points evenly distributed around a circle with a 50 cm radius centered on the seed robot. The starting orientations for the free robots
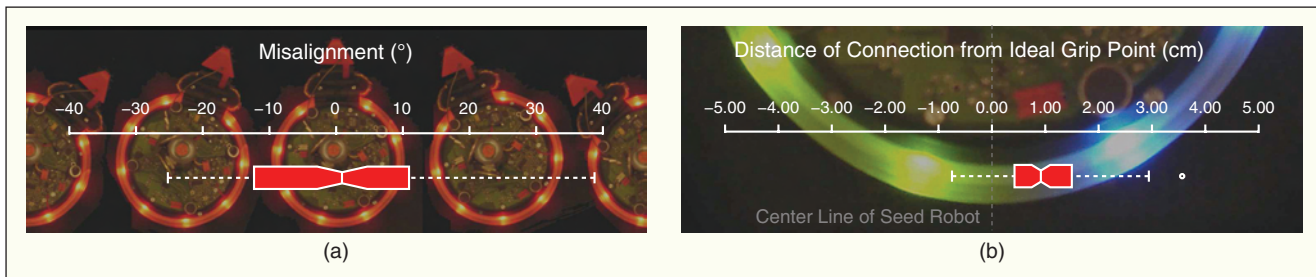
Figure 8. Precision of the directional self-assembly mechanism. (a) Angular precision measured by the mismatch between the alignment of the connecting robot and the alignment of the seed robot. (b) Positional precision measured by the lateral distance from the point at which the free robot connects to the ideal grip point. (In this case, the ideal grip point is the point where the LED ring of the seed robot intersects its center line.)
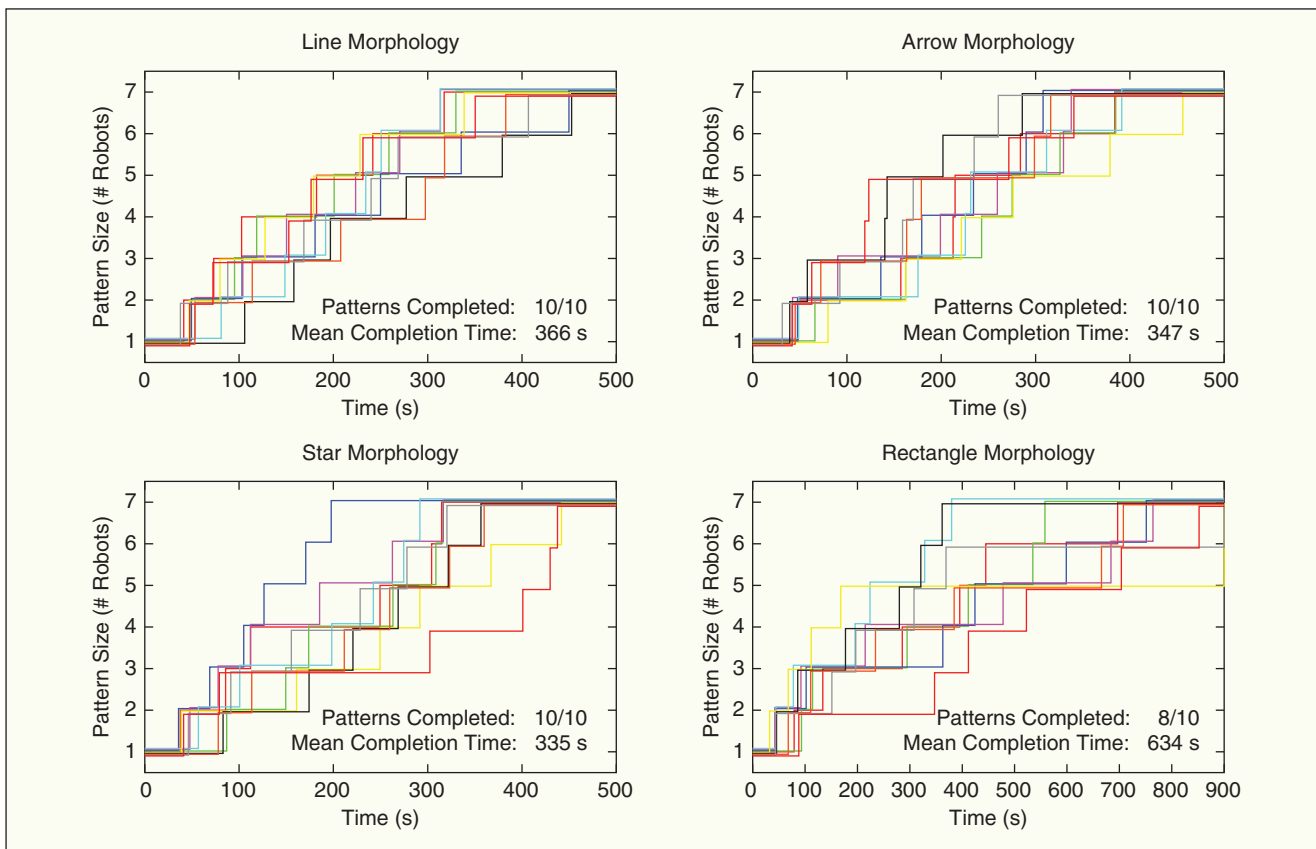
Figure 9. Morphology growth over time. Each colored line represents the growth of a single connected structure. There is one line for every trial conducted. Horizontal line segments indicate time intervals during which the number of connected robots in the structure remains constant. A vertical line segment indicates the moment when a free robot connects to the structure, after which a new horizontal line segment begins (corresponding to the new larger size of the structure).

were randomly sampled with replacement from four possible headings. We let each trial run until either all the robots were assembled to the connected structure or 15 min had passed. Completed examples of the four morphologies are shown in Figure 3.

We measured the time taken for each robot to connect to the structure. Figure 9 shows how the morphologies grew over time. Each morphology grown in every trial is individually represented by a different colored line. In 38 out of 40 trials, all six free robots successfully connected to the structure. In one of the rectangle morphology trials, a single robot failed to connect, and in another of the rectangle morphology trials, two robots failed to connect.

The rectangle morphology was more difficult to form than the other morphologies for two reasons. First, the connected robots are more densely distributed in this morphology. Thus, if a robot connects with a high angular misalignment or connects far from the ideal grip point, it can make it difficult or impossible for subsequent robots to connect. The rectangle morphology also relies on more sophisticated handshaking than the other morphologies— the connecting robot must determine its location in the structure during the course of the handshake (see Figure 7). In two of the rectangle morphology trials, this handshaking failed—the connecting free robot incorrectly determined its location in the structure. However, in both cases, the morphology continued to grow and, subsequently, reassumed a rectangular shape.

During experimentation, we observed that the incremental speed of morphology growth was dependent on the relationship between the number of connection slots open and the number of free robots available. Figure 10 displays the time intervals between successive connections for each morphology. Each successful connection from every trial is individually represented by a symbol corresponding to the type of morphology being grown.

A higher number of open connection slots allows the morphology to grow in parallel (if there are sufficient free robots available). In the arrow morphology, for example, after the first two robots have connected, there are usually two connection slots open. This makes it possible (although not inevitable) for two of the free robots to approach the open connection slots at the same time. This can be seen in Figure 10 by the short time intervals between arrow morphology connections 3–4. A similar mechanism explains the short time intervals between star morphology connections 4–5 and 5–6. After the fourth robot connects, all four connected robots open connection slots. This allows the fifth and sixth robots to find an open connection slot quickly and in parallel. (In ongoing work, we have also witnessed this phenomenon in experiments with larger numbers of simulated robots. Time intervals between star morphology connections 5–6, 6–7, 7–8 tend to be short whenever there are sufficient free robots to form connections in parallel.)

In the line morphology, the basic structure and mechanisms remain identical as the morphology grows. This is reflected in Figure 10 by the relatively consistent time intervals between successive line morphology connections. There is a slight gradual increase in the length of these time intervals with the later connections. This is due to the relative paucity of free robots. In these later stages, the growth of the line morphology can be delayed while a free robot traverses the length of the line to arrive at the connection slot.

Photographs and videos of experiments described in this article can be found at http://iridia.ulb.ac.be/supp/Iridia Supp2007-003/.

Conclusions and Future Research

We have demonstrated how autonomous mobile robots can self-assemble into global morphologies using only local information and local interactions. The algorithm is completely distributed, and each robot can assume any position in the final structure. Our directional self-assembly mechanism proved robust and precise. We achieved a high success rate in building four different morphologies using seven real robots.

In ongoing research, we are currently working with large swarms of simulated robots. Initial experiments indicate that the morphology-growing mechanism proposed in this article generalizes to arbitrary morphologies, and that it can scale to larger groups of robots. We plan to show that certain morphologies scale better than others, in particular, morphologies that allow for simultaneous expansion in multiple directions at the same time. The star morphology, for example, scales well as it allows up to four robots to connect simultaneously.

Another interesting direction for future research is adaptive self-assembly into specific morphologies. A group of robots could autonomously choose to self-assemble into different morphologies based on the parameters of their task. In an all-terrain navigation task, for example, the group could self-assemble into a line morphology to cross a ditch, while uneven or hilly terrain could trigger self-assembly into a dense morphology that provides stability.
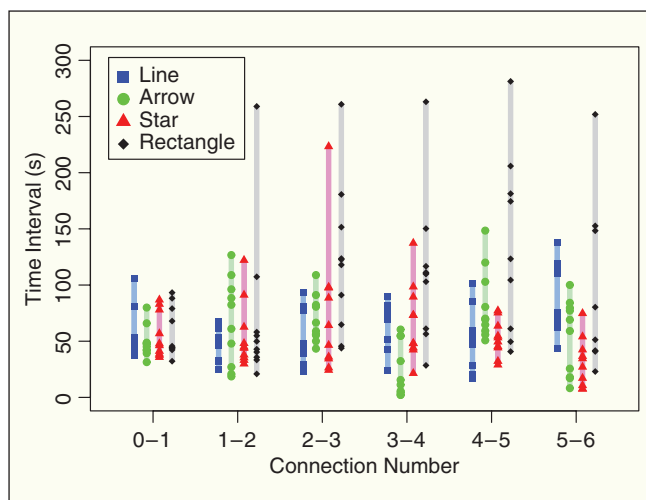
Figure 10. *Time intervals between connections. Each point represents a time interval between two successive connections in a single trial. There is one point for every successful connection in every trial. The time interval between connections 0 and 1 (0-1) is the time from the start of the trial to the time of the first connection. The colored bars indicate the range of values for a given morphology and time interval.*

Acknowledgments

Keywords

Self-assembly, morphology control, collective robotics, swarm intelligence.

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Anders Lyhne Christensen is currently a researcher at IRIDIA, CoDE, Université Libre de Bruxelles, Belgium. He has spent several years in the private sector and has worked on software projects ranging from three-dimensional acoustics to high performance computing. In 2002, he obtained his first master's degree in computer science and bioinformatics from Aalborg University, Denmark. Later that year, he received a Marie Curie Fellowship hosted by the Dependable Systems Group at the Universidade de Coimbra and Critical Software, Portugal. He completed his second master's degree at Université Libre de Bruxelles in 2005. He has published work on bioinformatics, high performance computing, and autonomous robotics. His current research interests are in dependable swarm robotics, autonomous self-assembly, and evolutionary robotics.

Rehan O'Grady is a researcher at the IRIDIA laboratory of the Université Libre de Bruxelles, Belgium. He graduated in 1999 from Edinburgh University with first class honours in mathematics and computer science. He received the Kevin Clark Memorial Prize, awarded each year to the top mathematics and computer science graduate. He subsequently worked in the software industry for several years. During his time at Micromuse PLC, he developed a system for monitoring usage outages in internet network services, which was subsequently patented. He received the Diplôme d'Études Approfondies (master's equivalent) from the Université Libre de Bruxelles in 2005. His current research interests are in swarm robotics and self-assembling robotic systems.

Marco Dorigo received the Laurea (master of technology) degree in industrial technologies engineering in 1986 and the doctoral degree in information and systems electronic engineering in 1992 from Politecnico di Milano, Milan, Italy, and the title of Agrégé de l'Enseignement Supérieur from the Université Libre de Bruxelles, Belgium, in 1995. From 1992 to 1993, he was a research fellow at the International Computer Science Institute of Berkeley, California. In 1993, he was a NATO-CNR fellow and from 1994 to 1996 a Marie Curie fellow. Since 1996 he has been a tenured researcher and is currently a research director of the FNRS, the Belgian National Fund for Scientific Research, and a research director of IRIDIA, the artificial intelligence laboratory of the Université Libre de Bruxelles. He is the inventor of the ant colony optimization metaheuristic. His current research interests include swarm intelligence, swarm robotics, and metaheuristics for discrete optimization. He is the Editor-in-Chief of the *Swarm Intelligence* journal. He was awarded the Italian Prize for Artificial Intelligence in 1996, the Marie Curie Excellence Award in 2003, and the Dr A. De Leeuw–Damry–Bourlart award in applied sciences in 2005. He is a Fellow of the IEEE and of the ECCAI.

Address for Correspondence: Anders Lyhne Christensen, IRIDIA, CoDE, Université Libre de Bruxelles, 50 Av. Franklin Roosevelt CP 194/6, 1050 Brussels, Belgium. E-mail: alyhne@iridia.ulb.ac.be.