Towards Adaptive Morphogenesis in Self-Assembling Robots

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***Abstract*—In this paper, we report on ongoing work on SWARMORPH which is a novel distributed mechanism that allows *s-bots*, autonomous mobile robots from the swarm-bot platform, to self-assemble into specific morphologies. We have abstracted primitive behaviors such as *random walk*, *invite connection* and *disconnect* into a language (SWARMORPH-script). We have furthermore implemented simple color-based communication that enables connected robots to send strings to one another. In [6], we demonstrated how SWARMORPH-script allows specific morphologies to be constructed, how the size of a morphology can be regulated, and how multiple morphologies can be assembled. The aim of our ongoing research is to give the robots the capacity to autonomously decide when to self-assemble and what morphology to form based on environmental contingencies. We discuss a possible scenario in which adaptive morphogenesis could be demonstrated on real robots in the near future.**

I. INTRODUCTION

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 pre-specified 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.

The field of modular self-reconfigurable robotic systems is dedicated to the study of systems with morphological flexibility (for an overview see [24]). The components of such systems can autonomously reorganize into different configurations. Several different hardware architectures (lattice, chain/tree, mobile) and many different implementations and control mechanisms have been proposed [4], [14], [18], [23]. However, in the majority of current implementations, the components are either manually pre-assembled or rely on their environment (be it natural or manmade) to provide the energy required for independent movement. Once assembled, most existing systems are furthermore 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 pre-connected self-reconfigurable systems. Several architectures have been proposed, which have been implemented with varying degrees of success [3], [7], [11], [12], [13]. However, none of the existing systems display any meaningful control over the morphology of the connected entity formed through the self-assembly process.

Another related research field is formation control. Here, groups of robots steer themselves into one or more pre-specified formations [1], [8], [15], [16], [21]. 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 paper, we report on ongoing work with SWARMORPH - 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 local visual perception only. None of the robots have any predefined position in the final morphology. Robots that are part of the connected entity indicate where new robots should attach in order to grow the local structure appropriately. Previously studied algorithms for morphology growth have been tested using abstracted simulated robotic models [2], [22]. The aim of our work on SWARMORPH is to give real robots the capacity to decide when to self-assemble and what morphology to form depending on environmental contingencies.

II. HARDWARE PLATFORM

For our experiments, we use the innovative swarm-bot robotic platform [17] built by Francesco Mondada's group at the Laboratoire de Systèmes Robotiques of the École Polytechnique Fédérale de Lausanne. The platform consists of a number of mobile autonomous robots called *s-bots* (see Fig. 1) that are capable of forming physical connections with each other. Each *s-bot* is equipped with an XScale CPU running at 400 MHz, a number of sensors including an omni-directional camera, infrared ground sensors, proximity sensors, and light sensors. Physical connections between *s-bots* are established by a gripper-based connection mechanism. Each *s-bot* is surrounded by a semi-transparent ring that can be grasped by other *s-bots*. *S-bots* can advertise their location and/or internal state by means of eight sets of RGB-colored LEDs distributed around the inside of their semi-transparent ring.

The swarm-bot platform has been used for various studies in swarm intelligence and collective robotics, see for

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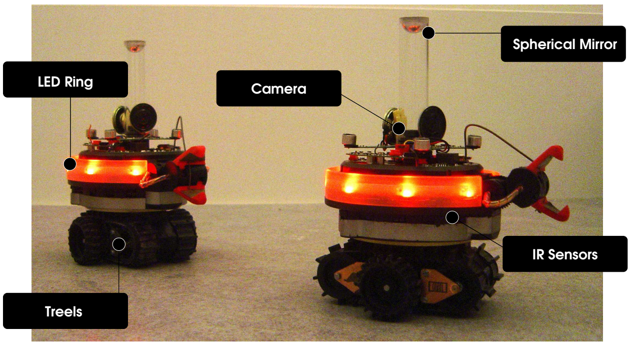

Fig. 1. *S-bot*: An autonomous, mobile robot capable of forming physical connections with other *s-bots*.

instance [9], [10]. Collaborating *s-bots* have been shown capable of overcoming steep hills and capable of transporting heavy objects [12], [20] – both are examples of tasks that a single *s-bot* could not complete individually.

III. MOTIVATION AND PREVIOUS WORK

In a previous work [5], we demonstrated the self-organized growth of specific morphologies. To grow the morphology, an *s-bot* that is already connected to the morphology illuminates a particular configuration of LEDs to indicate a point on its body where another non-attached *s-bot* should grip and a corresponding orientation which the gripping *s-bot* should assume. The newly connected robot in turn attracts other robots by lighting up its own colored LEDs. In this system, each morphology was defined via a set of simple rules. As robots would attach to the morphology, they would apply those rules in order to extend the structure appropriately. However, the absence of symbolic communication, as well as the homogeneity of the robotic controllers, meant that each newly connected robot had to follow the same pattern extension rules, with the result that only repeating structures were possible.

In [6], we extended the system in two ways: firstly, we augmented the system's communication capabilities to allow for the transmission of strings between physically connected robots. Secondly, we abstracted basic behaviors such as *random walk*, *invite connection*, and *disconnect*, into a set of control primitives. We used these control primitives to build a morphology creation language (SWARMORPH-script) that can be executed on real robots. The language allows for explicit high-level expression of distributed rules for morphology growth. When a new robot connects to the morphology, it initiates communication with the robot to which it connected. Through this communication, the newly connected robot receives instructions about how to extend the local structure. Following these instructions, the newly connected robot in turn attracts other robots by lighting up its own colored LEDs. When a subsequent new robot attaches, it once again initiates communication, and is told in turn how to extend the structure. As this process repeats itself, the morphology grows accordingly.

A. The Color-based Communication Mechanism

The *s-bot* has no hardware dedicated to local point-to-point communication and we have therefore implemented a simple protocol based on visual communication: We use the three colors red, green and blue. Each time a bit is transmitted, the sending robot changes the illumination of its LEDs. The color green represents a '0' bit, blue represents a '1' and red represents a repeat bit. We rely on acknowledgment to distinguish adjacent bits. The receiver acknowledges receipt of each bit by lighting up its LEDs to match the color of the sender's LEDs. Once the receipt of a bit has been acknowledged, the sender transmits the next bit. This acknowledgement mechanism necessitates our use of the dedicated color for a repeat bit. When transmitting a substring of two or more bits of the same value, every other bit will be represented by the color red (starting from the second bit). For more details, see [6].

B. SWARMORPH-Script

SWARMORPH-script is a simple language in which we can describe distributed morphology control at a high level. Below we provide a summary of the primitives available in SWARMORPH-script (see [6] for more details):

- `RandomWalk()`: Random walk until either an obstacle is encountered or a robot inviting a connection is seen.
- `Phototaxis()`: Perform phototaxis until an obstacle has been encountered or overcome.
- `Notify()`: Notify a physically connected robot.
- `OpenConnSlot()`: Invite a connection at a certain location.
- `SearchForConnSlot()`: Find and connect to a robot inviting a connection.
- `SendRuleID(rule-id)`: Send the ID of a rule.
- `ReceiveRuleID()`: Receive the ID of a rule.
- `SendScript()`: Send a SWARMORPH-script.
- `ReceiveScript()`: Receive a SWARMORPH-script.
- `ExecuteReceivedScript()`: Execute a received SWARMORPH-script.
- `Disconnect()`: Open the gripper to disconnect from the morphology.
- `Retreat()`: Retreat for a certain amount of time.
- `if, then, end`: Branch based on the type of obstacle encountered or based on the rule ID received.

In [6], we demonstrated how 1) specific morphologies could be constructed, 2) multiple independent morphologies could be formed, and 3) how the transmission of entire scripts gives the robots the capacity to participate in the formation of morphologies of which they had no a priori knowledge. An example of a morphology autonomously formed by a group of robots executing SWARMORPH-script can be seen in Fig. 2. The SWARMORPH-script executed by all the robots is shown in Script 1. All robots execute the same SWARMORPH-script. Initially, the robots perform random walk. When one of the robots encounters an obstacle (in this case a dark patch on the floor which is perceived as a hole by the *s-bots*), the robot illuminates its LEDs in order to invite another robot to connect (it *opens a connection slot*). When a random walk-

Fig. 2. Two mini-squares: the result of running Script 1 on eight real *s-bots*.

ing robot sees that another robot is inviting a connection, it ceases to random walk and tries to physically connect to the inviting robot. When a successful connection has been formed, communication is initiated. In the example shown in Script 1, only rule IDs are communicated, however, whole SWARMORPH-scripts can be communicated and subsequently executed by the receiving robot.

Script 1: Mini-squares - an example of a SWARMORPH-script for generating multiple independent morphologies.

```
RandomWalk();
if hole-detected then
    OpenConnSlot(left);
    SendRuleID(1);
    StopExecution();
end
if conn-slot-detected then
    SearchForConnSlot();
    ReceiveRuleID();
    if $receivedruleid = 1$ then
        OpenConnSlot(right);
        SendRuleID(2);
    end
    if $receivedruleid = 2$ then
        OpenConnSlot(right);
        SendRuleID(3);
    end
    if $receivedruleid = 3$ then
        OpenConnSlot(back);
        SendRuleID(4);
    end
    if $receivedruleid = 4$ then
        Disconnect;
        Retreat(5 s);
        OpenConnSlot(left);
        SendRuleID(1);
    end
end
```

In [19], we demonstrated how a group of *s-bots* could autonomously self-assemble and then reconfigure between different morphologies.

At this point, we are thus able to form specific morphologies and to dynamically change the morphology of the connected robotic entity. We are yet to demonstrate that a connected robotic entity can do something useful once it has been formed. Overcoming different obstacles such as rough terrain and a trough are suitable candidate tasks. A single robot could topple on rough terrain, or fall into a trough. If the robots self-assemble into an appropriate morphology (i.e., a stable dense morphology to overcome the rough terrain, or a longer line morphology to overcome the trough) they would have a better chance of overcoming the obstacle.

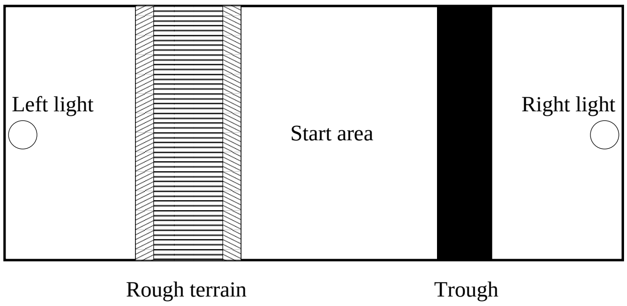

Fig. 3. Environment with two types of obstacles and two light sources. Only on of the light sources are lit during an experiment.

IV. Towards Adaptive Morphogenesis

In this section, we describe an experiment with which we intend to show adaptive morphogenesis. We have designed our experiment so that the robots must autonomously determine when to self-assemble and which morphology to form.

The environment is rectangular and contains two types of obstacles—rough terrain and a trough—and two light sources (see Fig. 3).

At the beginning of the experiment, 4-6 robots are placed in the center of the environment and one of the two light sources (chosen randomly) is turned on while the other remains off. Initially, the robots are not physically connected to each other. The robots task is to reach the illuminated light source. To do this, they must overcome whichever of the two obstacles is between them and the illuminated light.

In order to cross the rough terrain, the robots need to self-assemble into a dense morphology, while the robots need to self-assemble into a linear morphology to be able to cross the trough. At the beginning of an experiment, the robots are unaware of which of the two obstacles they need to overcome (which depends on which of the two lights is switched on). They thus have to explore the environment and autonomously determine which morphology to form based on the obstacle they encounter.

An experiments therefore starts with the robots performing individual phototaxis. Once an obstacle is encountered they self-assemble, using the `if, then, end` construct, into the appropriate morphology, which is dependent on the obstacle encountered. Once self-assembled, the robots can move across the obstacles. We are in the process of building the experimental environment and we expect to have results shortly.

V. CONCLUSIONS

In this paper, we have described ongoing work on a distributed morphology generation mechanism called SWARMORPH. In the first instantiation, morphologies were generated using repeated application of local rules. We later augmented the system with local point-to-point communication capabilities and we abstracted basic behaviors as primitives in a language called SWARMORPH-script. Throughout our work with SWARMORPH, we have demonstrated morphology generation on real robotic hardware. Our current efforts are focused on leveraging our morphology generation mechanism to add functional value to a group of real robots. We described the experimental setup in which we intend to demonstrate adaptive morphogenesis on real robots.

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