Cooperation in a Heterogeneous Robot Swarm through Spatially Targeted Communication

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Abstract. We consider a heterogeneous swarm robotic system composed of wheeled and aerial robots called foot-bots and eye-bots, respectively. The foot-bots are able to physically connect to one another autonomously and thus form collective robotic entities. Eye-bots have a privileged overview of the environment since they can fly and attach to metal ceilings. In this paper, we show how the heterogeneous swarm can benefit from cooperation. By using so-called *spatially targeted communication*, the eye-bot is able to communicate with selected groups of foot-bots and instruct them on how to overcome obstacles in their path by forming morphologies appropriate to the obstacle encountered. We conduct experiments in simulation to quantify separately the benefits of cooperation and of spatially targeted communication.

1 Introduction

We use a heterogeneous swarm robotic system consisting of two types of robots: foot-bots and eye-bots (see Fig. 1a and Fig. 1b). The foot-bots are capable of autonomous self-assembly which means that they can make physical connections with one another and form collective robotic entities. In this paper, we focus on the task of navigating through an environment that contains a gap. Depending on the width of the gap, the foot-bots may need to self-assemble into a collective robotic entity to successfully overcome the gap.

In a previous study [10], a team of wheeled robots autonomously self-assembled into different morphologies to solve different tasks, one of which was a gap crossing task similar to the one considered in this paper. In that study, however, the solution to each task was preprogrammed. For example, the wheeled robots did not have the sensory capabilities to estimate the width of a gap. Therefore, on encountering a gap, they would always self-assemble into a four robot line morphology irrespective of the width of the gap. In this paper, we present an approach for cooperation between aerial and wheeled robots that enables self-assembling robots to adaptively generate appropriate morphologies to a priori unknown tasks.

In the task we consider, the heterogeneous swarm is located in an environment consisting of a start zone, a target zone, and a gap that separates the two zones

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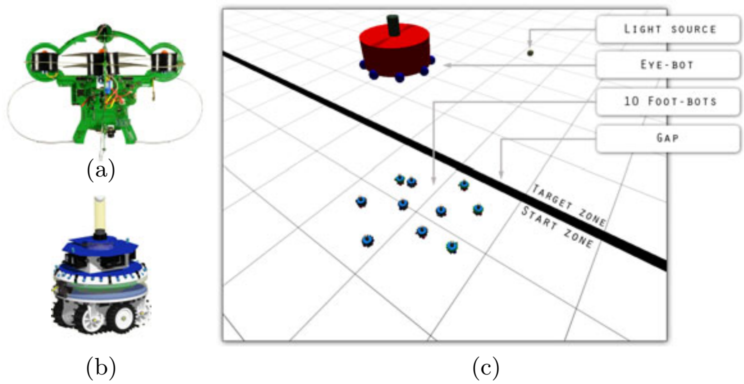


Fig. 1. The heterogeneous swarm robotic system and the task considered in this study. (a) The prototype of the eye-bot. (b) A CAD model of the foot-bot. Both robot types are being developed at EPFL within the framework of the Swarmanoid project. More information about the project is available at http://www.swarmanoid.org. (c) A depiction of the task considered. The dark strip represents the gap which separates the arena into a start zone and a target zone. The circular object shown in the target zone is the light source. An eye-bot and 10 foot-bots are visible in the start zone.

(see Fig. 1c). A light source perceivable by the foot-bots is located in the target zone. At the start of each experiment, 10 foot-bots are placed at random positions with random orientations within a square area of 2 m x 2 m in the start zone. The foot-bots use their light sensors to detect and drive to the light source in the target zone. They use the ground sensors to avoid falling into the gap. An eye-bot is assumed to be attached to the ceiling in the start zone using its system of magnets. It is able to perceive all the foot-bots in the start zone. The eye-bot can estimate the width of the gap by using its pan-and-tilt camera and the on-board image processing software. To reach the target zone, the foot-bots may need to connect to each other to form a collective morphology, such as a line morphology [2]. Note that the minimal length of such a line morphology (i.e., the number of foot-bots in the line) that guarantees a safe crossing of the gap depends on the width of the gap. In this study, we vary the width of the gap between 5 cm, 10 cm, 15 cm and 25 cm. These different gap widths require the foot-bots to form a line morphology of 1, 2, 3 and 4 foot-bots respectively. The task is considered to be completed when the final foot-bot of the line morphology has crossed the gap and reached the target zone.

To enable cooperation in the heterogeneous swarm, we use a combination of techniques developed in previous research. Firstly, the eye-bot establishes *spatially targeted communication* [9] with a selected group of foot-bots. Secondly, the eye-bot sends morphology growth instructions to these foot-bots in the form of SWARMORPH-script [2] instructions. Both spatially targeted communication and SWARMORPH-script have been successfully tested on real robotic hardware in previous studies, see [9] and [2], respectively. Our approach does not require any form of global information.

At the time of writing, the heterogeneous swarm robotic system is still under development. We therefore use a custom physics-based simulator named ARGoS [13] to study separately the benefits of cooperation between the two robot types and spatially targeted communication.

2 Related Work

Most previous studies on cooperation in heterogeneous systems have focused on tightly-coupled heterogeneous teams, see for instance [12,18,4]. In these and other similar multirobot systems, researchers have used communication and/or localization modalities such as wireless ethernet [17], infrared [7] or ultrasound [15]. In this study, we consider a heterogeneous swarm robotic system composed of numerous wheeled and aerial robots, see for instance [14]. We use on-board LEDs and cameras for communication between the foot-bots and the eye-bots. The foot-bots can also communicate with each other using a communication system based on infrared and radio [16].

Many researchers have designed and studied systems that can reconfigure or self-assemble into physically connected structures [6]. To date, several hardware architectures for self-propelled self-assembling robotic systems have been proposed and implemented [3,5]. In this study, we use foot-bots which are self-propelled, fully autonomous and can self-assemble. The performance benefits of different self-assembly strategies for similar robots has been studied previously [11], however the study was conducted on a homogeneous system and morphology control was not considered. For self-assembling and self-reconfigurable systems, several different control approaches have been proposed [1,8]. In this work, we use a language called SWARMORPH-script [2] that allows target morphologies to be described as distributed control logic.

3 Methodology

We achieve cooperation using two mechanisms developed in previous research. Firstly, the eye-bot establishes a *spatially targeted communication* [9] link with a group of foot-bots that is appropriately located (i.e., near the gap) and has an appropriate size (i.e., the precise number of foot-bots required to cross the gap). Secondly, the eye-bot instructs these selected foot-bots to form the line morphology (i.e., target morphology) that will allow them to cross the gap [2].

In [9], a LEDs and camera-based communication is used by a robot to first narrow down the number of potential recipients of a broadcast message to a single *seed* robot. This one-to-one communication link is then expanded to include the closest neighbors of the seed robot such that a one-to-many commnication link of a desired size can be created. Such a dedicated communication link enables the eye-bot to ensure that subsequently broadcasted messages will only be processed

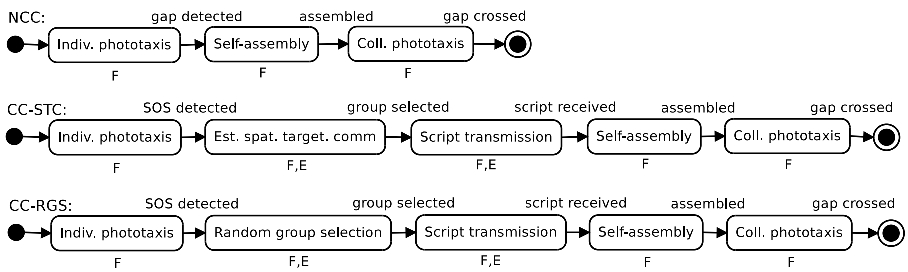


Fig. 2. Decomposition of control strategies into phases. Phases only involving foot-bot are marked 'F', phases involving foot-bot eye-bot cooperation are marked 'F.E'. i) NCC: non-cooperative control, ii) CC-STC: cooperative control with spatially targeted communication and iii) CC-RGS: cooperative control with random group selection. NB 'Indiv. phototaxis' = 'Individual phototaxis', 'Coll. phototaxis' = Collective phototaxis, 'Est. spat. target. comm.' = 'Establishing Spatially Targeted Communication'.

by the selected group of foot-bots even though other foot-bots may also be able to receive the messages.

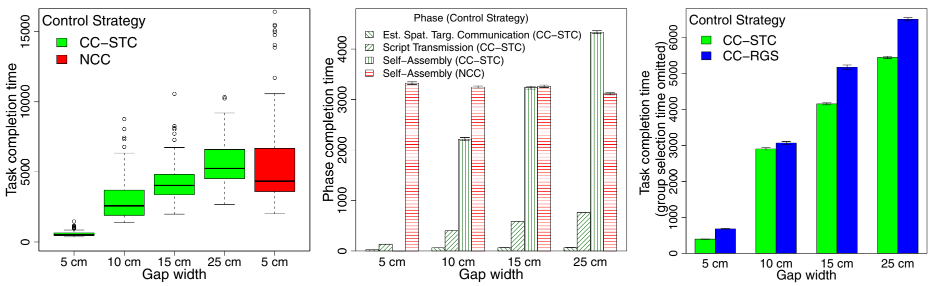
We use such dedicated communication links to let the eye-bot send instructions to the foot-bots on how to self-assemble into the target morphology. These instructions are sent in SWARMORPH-script [2]. SWARMORPH-script is a language for distributed self-assembly and morphology control for autonomous self-assembling robots. The eye-bot uses a protocol based on LEDs and camera to send the SWARMORPH-script required to generate the target morphology. Each foot-bot that receives such a SWARMORPH-script can execute this received control logic. In this manner, the foot-bots do not need to have any a priori knowledge about possible morphologies required or even possible tasks.

4 Experiments and Results

We ran simulation-based experiments using three different control strategies of the heterogeneous swarm. For each combination of gap size and control strategy, we ran 100 repetitions. By comparing the task completion times of the three strategies, we first analyze the benefits of cooperation through spatially targeted communication, and then isolate the benefits of spatially targeted communication. Videos of the experiments conducted are available online at: `http://iridia.ulb.ac.be/supp/IridiaSupp2010-007/`.

4.1 The Three Control Strategies

The three strategies are presented in Fig. 2. The simplest strategy is **NCC** — non-cooperative control. In this strategy, the foot-bots operate without cooperating with the eye-bot. They initially move towards the light and form a four robot line morphology when they encounter any gap (irrespective of the width



(a) (b) (c)

Fig. 3. Results of the experiments showing task/phase completion times in simulation steps. In Fig. 3b and 3c, the whiskers represent the standard deviation. (a) Box-and-whisker plot comparing CC-STC and NCC for varying gap widths. (b) Bar-plot showing a breakdown of the time spent in different phases of CC-STC and NCC. (c) Completion times of CC-STC and CC-RGS minus the time taken to form the group.

of the gap). The foot-bots are pre-loaded with the SWARMORPH-script instructions to form the morphology and cross the gap by performing collective phototaxis.

The methodology presented in this work is implemented in **CC-STC** — cooperative control with spatially targeted communication. In this strategy, the foot-bots initially move towards the light until the eye-bot initiates the process to establish a spatially targeted communication link with the minimal number of foot-bots required to form the target morphology. The communication link is established with foot-bots that are favorably located (i.e., close to the gap) to solve the task. Subsequently, a SWARMORPH-script is sent to these foot-bots. Once the target morphology is generated, the foot-bots perform collective phototaxis to cross the gap.

The final strategy is **CC-RGS** — cooperative control with random group selection. This strategy allows us to isolate the performance benefits of spatially targeted communication. The strategy is identical to the CC-STC strategy, except that instead of selecting the foot-bots to form the target morphology on the basis of their favorable location, the eye-bot randomly selects the minimal number of foot-bots required to form the target morphology.

4.2 Benefits of Cooperation in the Heterogeneous Robot Swarm

We compare the task execution times of strategies NCC and CC-STC to analyze the benefits of cooperation through spatially targeted communication. The results are shown in Fig. 3a. In the case of NCC, we have only plotted the results of the narrowest gap (5 cm), as the task completion times between the various gap widths did not prove to be significantly different for the NCC strategy.

According to the results in Fig. 3a, the median task completion times of CC-STC are 507, 2590 and 4032 simulation steps for gaps of width 5, 10 and

15 cm, respectively. This means that CC-STC was 88%, 40% and 7% faster when compared to the median task completion value of NCC (4340 simulation steps). This is due to the fact that in CC-STC, the length of the line is optimal with respect to the width of the gap. However, for the widest gap (25 cm), NCC is shown to be faster than CC-STC. Intuitively, this could have been expected given that both control strategies form a line of four robots close to the gap, but in the case of CC-STC, instructions have to be first received from the eye-bot before the self-assembly process can start and therefore requires more time. Results also show that NCC has several outlier trials that take very long to complete. This is because in the NCC strategy all foot-bots in the experiment are allocated to construct the morphology and some non-connected foot-bots can interfere (sometimes severely) with the collective phototaxis of the complete morphology.

In Fig. 3b, a breakdown of the time spent in the different phases of each control strategy is shown: (i) establishing spatially targeted communication (CC-STC), (ii) transmitting the SWARMORPH-script (CC-STC) (iii) self-assembly (CC-STC), (iv) self-assembly (NCC). The results show that with the increasing size of the morphology, and therefore with the increasing length of the SWARMORPH-script that has to be transmitted, the transmission time increases. However, this communication overhead of CC-STC would become negligible if a communication modality with higher bandwidth (such as WiFi) was used. The results also show that when a line of equal length is formed in both control strategies, as in the case of 4 foot-bots, the self-assembly process of CC-STC requires on average 39% more time than that of NCC. This can be explained by the fact that in NCC there are more robots attempting to connect to a connection-inviting foot-bot which in turn leads to faster morphology formation. On the other hand, CC-STC deals with the resources optimally by only allocating precisely the required number of robots needed for the self-assembly process. The decision involving this trade-off between faster morphology formation times and optimal resource allocation may depend on the task and/or the priorities of the system.

4.3 Benefits of Spatially Targeted Communication

To isolate the benefits of spatially targeted communication, we compare the task completion times of strategies CC-STC and CC-RGS. Note that both control strategies select the seed foot-bot using the same technique. However, the selection of further foot-bots required in the target morphology is different. Therefore, in order to maintain objectivity in the comparison, in this set of experiments the time spent to select the non-seed foot-bots was omitted for both control strategies. The results are plotted in Fig. 3c.

As the results show, CC-STC was on average faster than CC-RGS independent of the width of the gap. This is because a morphology formed next to the gap require less time to reach and cross the gap than a morphology formed at a random place in the environment. We expect that this difference in terms of task completion time would be even greater for larger start zones.

Additionally, we also studied the difference in completion times between CC-STC and CC-RGS in the presence of obstacles: the foot-bots were placed in the start zone within an area of 2 m x 2 m surrounded by walls on three sides to adjoin the gap on the fourth side. We found that the presence of the walls had no significant impact on the completion time of CC-STC in which the eye-bot selects the seed and the group in favorable locations (i.e., always close to the gap and away from the walls). For the CC-RGS control strategy, on the other hand, the presence of walls had a significant negative impact on performance. When the randomly selected seed (which initiates the morphology growth process) happened to be located close to one of the walls, it could be difficult or even impossible for other foot-bots to physically connect to the seed. As a result, the task was not solved in our experiments with the CC-RGS control strategy in 13%, 29% and 34% of the experiments for the line morphology composed of 2 foot-bots, 3 foot-bots and 4 foot-bots, respectively.

5 Conclusions and Future Work

In this paper, we have demonstrated how aerial robots and wheeled robots can cooperate to solve different instances of a gap crossing task in an adaptive manner. Compared to a non-cooperative strategy, the cooperative strategy was shown to be more efficient in terms of resource allocation as the aerial robot recruited only the necessary robots based on the width of a gap. Furthermore, the cooperative strategy led to faster task completion times in the environment in which fewer than four connected robots could cross the gap. We also demonstrated the benefits of spatially target communication. When the aerial robot selected wheeled robots based on their location and based on their mutual proximity to each other, the time required to self-assemble and to cross the gap was lower than when robots were randomly selected.

Our short-term goal is to repeat the experiments shown in this paper on real robotic hardware. In ongoing research, we are investigating other cooperation mechanisms between aerial and wheeled robots, in particular where the cooperation is more bidirectional. In this study, the wheeled robots passively received instructions from the aerial robots. In the future, wheeled robots on the ground could ask an aerial robot to find additional robots for a given task, and multiple aerial robots could allocate and share groups of wheeled robots dynamically.

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References

1. Butler, Z., Kotay, K., Rus, D., Tomita, K.: Generic decentralized control for lattice-based self-reconfigurable robots. Int. Jour. of Rob. Res. 23(9), 919–937 (2004)
2. Christensen, A.L., O'Grady, R., Dorigo, M.: SWARMORPH-script: A language for arbitrary morphology generation in self-assembling robots. Swarm Intelligence 2(2-4), 143–165 (2008)
3. Damoto, R., Kawakami, A., Hirose, S.: Study of super-mechano colony: concept and basic experimental set-up. Adv. Robotics 15(4), 391–408 (2001)
4. Dias, M.B., Zlot, R., Kalra, N., Stentz, A.: Market-based multirobot coordination: A survey and analysis. Proc. of the IEEE 94(7), 1257–1270 (2006)
5. Fukuda, T., Buss, M., Hosokai, H., Kawauchi, Y.: Cell structured robotic system CEBOT: Control, planning and communication methods. Rob. and Auton. Syst. 7(2-3), 239–248 (1991)
6. Groß, R., Dorigo, M.: Self-assembly at the macroscopic scale. Proc. of the IEEE 96(9), 1490–1508 (2008)
7. Gutiérrez, A., Campo, A., Dorigo, M., Amor, D., Magdalena, L., Monasterio-Huelin, F.: An open localization and local communication embodied sensor. Sensors 8(11), 7545–7563 (2008)
8. Klavins, E., Ghrist, R., Lipsky, D.: A grammatical approach to self-organizing robotic systems. IEEE Trans. on Autom. Cont. 51(6), 949–962 (2006)
9. Mathews, N., Christensen, A.L., Ferrante, E., O'Grady, R., Dorigo, M.: Establishing spatially targeted communication in a heterogeneous robot swarm. In: 9th Int. Conf. on Auton. Agents and Multiagent Syst. (AAMAS 2010), pp. 939–946. ACM, New York (2010)
10. O'Grady, R., Christensen, A.L., Pinciroli, C., Dorigo, M.: Robots autonomously self-assemble into dedicated morphologies to solve different tasks (extended abstract). In: 9th Int. Conf. on Auton. Agents and Multiagent Syst. (AAMAS 2010), pp. 1517–1518. ACM, New York (2010)
11. O'Grady, R., Groß, R., Christensen, A.L., Dorigo, M.: Self-assembly strategies in a group of autonomous mobile robots. Auton. Robots 28(4), 439–455 (2010)
12. Parker, L.: ALLIANCE: an architecture for fault tolerant multirobot cooperation. IEEE Trans. on Rob. and Autom. 14(2), 220–240 (1998)
13. Pinciroli, C.: The Swarmanoid Simulator. Tech. Rep. TR/IRIDIA/2007-025, IRIDIA, Université Libre de Bruxelles, Brussels, Belgium (2007)
14. Pinciroli, C., O'Grady, R., Christensen, A.L., Dorigo, M.: Self-organised recruitment in a heterogeneous swarm. In: 14th Int. Conf. on Adv. Rob. (ICAR 2009). Proceedings on CD-ROM, paper ID 176, p. 8 (2009)
15. Rivard, F., Bisson, J., Michaud, F., Létourneau, D.: Ultrasonic relative positioning for multi-robot systems. In: IEEE Int. Conf. on Rob. and Autom., pp. 323–328. IEEE Press, Piscataway (2008)
16. Roberts, J.F., Stirling, T.S., Zufferey, J.C., Floreano, D.: 2.5d Infrared Range and Bearing System for Collective Robotics. In: IEEE/RSJ Int. Conf. on Int. Rob. and Syst. (IROS 2009). IEEE Press, Piscataway (2009)
17. Stentz, A.T., Kelly, A., Herman, H., Rander, P., Amidi, O., Mandelbaum, R.: Integrated air/ground vehicle system for semi-autonomous off-road navigation. In: AUVSI Unmanned Syst. Symp. (2002)
18. Sukhatme, G., Montgomery, J., Vaughan, R.: Experiments with aerial-ground robots. In: Robot Teams: From Diversity to Polymorphism, pp. 345–367. AK Peters, Wellesley (2001)