Physical connections and cooperation in swarm robotics

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Abstract. We describe a new multi-robot system, named SWARM-BOTS, that exploits physical inter-connections to solve tasks that are impossible for a single robot. This is for instance the case of passing large gaps or high steps in all-terrain conditions. In order to achieve this type of autonomous collective operations, the design of the type of connection, as well as its sensors and actuators, plays a key role. This paper presents the choices made in the SWARM-BOTS project and the know-how collected until now. The requirements for autonomous operation and mobility of each robots have led to the development of a connectivity very different those found in self-reconfigurable robots. Some of the solutions employed for this problem are inspired upon physical connectivity of social insects. We also illustrate with two experiments how sensors and actuators allow autonomous operation in connection, release as well as passive and active exploitation of inter-robot degrees of freedom (DOF).

1 Introduction

The goal of the SWARM-BOTS[1] project is to explore new hardware and software aspects of swarm intelligence [2]. A *swarm-bot* is composed of several small mobile robots (with a diameter of 10 cm), called *s-bots*, able to autonomously self-assemble into bigger entities, called *swarm-bots* [7, 6]. A peculiar feature of the Swarm-bot is that s-bots can exploit rich connection devices to self-assemble into various configurations, help each other, perform collective transportation, and even communicate to each other. This feature, which is exploited by several social insects [1], provides an additional dimension to collective robotics where interactions among robots are often virtual or take place through pushing actions.

One of the most critical aspects of this project is clearly the connection between the robots, which is also the core of the innovation. The problem of interconnecting robot modules has already been addressed by many researchers in the field of self-reconfigurable robots, leading to many design solutions as shown in figure 1. For example the MTRAN and the PolyBot modular robots display some of the most interesting results and use efficient connection solutions. The MTRAN design [4] is based on permanent magnets for connection and on shape memory alloy coils combined with non-linear springs for disconnection (connection type d. in figure 1). PolyBot [10] has connection plates with four grooved pins that match four holes on the opposing plate and are grabbed by a latching mechanism that can be later

[1] www.swarm-bots.org

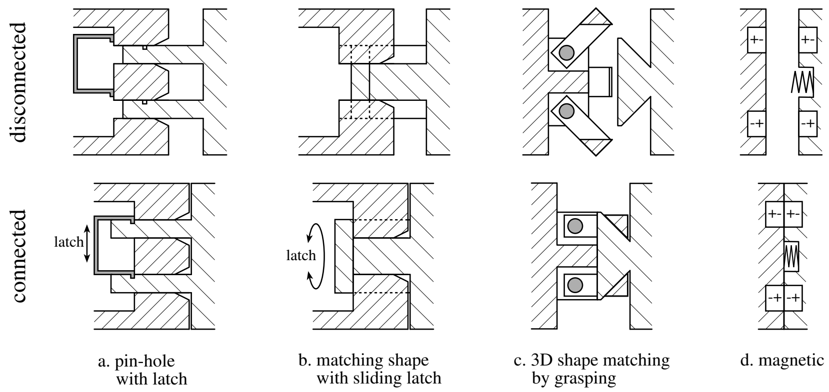

Figure 1: Schematic representation of the four main types of connections found in self-reconfigurable robots.

released by a shape memory alloy mechanism (connection type a. in figure 1). Both MTRAN and Polybot have hermaphroditic connections, which implies only one type of mechanical connector. Other systems, such as CONRO [8], have pin-based connections too but are not hermaphrodite i.e. need male and female connectors. Finally, some modular robots such as I-CES [9] and the Molecule robot [5] have structures with two types of modules, one responsible for the structure itself, the other dedicated only to connectivity. Both I-CES and Molecule have male-female connection mechanisms based on matching of complex shapes (connection type b. for I-CES and c. for Molecule as illustrated in figure 1).

All the connection methods mentioned above, with the exception of the MTRAN system, are based on penetration and shape matching, similar to the model of a pin in a hole. This type of connection is mechanically very stable but needs very good alignment during approach. The MTRAN system is based on flat contact surfaces and has therefore better tolerances to misalignment. The disadvantage of this type of solution is that it does not withstand lateral forces by mechanical parts but only by friction. Despite the better positioning tolerance of the MTRAN system, all these systems require a relatively accurate positioning. This constraint is not a limitation because modules of self-reconfigurable robots move always inside the structure, thus allowing accurate positioning.

In the case of two mobile robots interconnecting with each other, the common structure does not exist. The connection must be therefore much more tolerant to alignment errors still providing good mechanical robustness. The only available multi-robot concept with physical connections is the Millibot train [3]. The Millibot train design is based on a pin-hole concept for strong mechanical stability, but this makes it very hard to perform autonomous self-connection. Furthermore, the lack of sensors on the connecting points makes autonomous self-connection almost impossible in our opinion.

In the SWARM-BOTS project we have considered mechanical robustness in the context of an autonomous connection. This has resulted in the choice of a system based on 2D shape matching without penetration. This makes the connection less mechanically rigid, but simplifies the connection procedure providing large tolerance to positioning and alignment. This solution, which looks like a gripper, is also similar to the mechanisms used by animals for this type of tasks, such as mandibles in ants or bees.

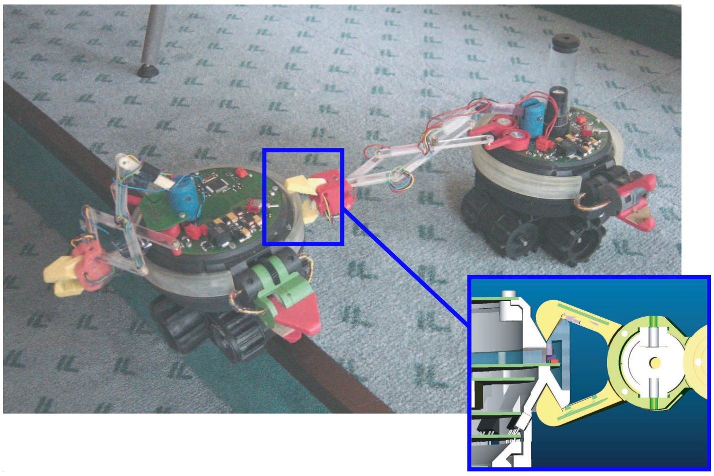

Figure 2: Two s-bots connected by mean of the flexible gripper with detail on matching between gripper and grasping ring.

2 Mechanical concept and implementation

In SWARM-BOTS, the connection between s-bots is based, as mentioned above, on 2D shape matching without penetration. The connection mechanism is a gripper that matches the shape of a ring present on the main body of the robot. Figure 2 shows two connected s-bots with the detail of shape matching between gripper and ring. This solution allows a robot to grasp another robot all around its body.

Each s-bot is equipped with two grippers. One is supported by a rigid structure with one degree of freedom (DOF) and is called *rigid gripper*. The second one is placed at the end of a flexible arm with three DOF and is called *flexible gripper*. The two grippers play very different roles in swarm-bot configurations. The rigid gripper allows to create very stable multi-robot structures with one active degree of freedom on each inter-robot link. The flexible gripper instead allows the creation of flexible swarm configurations that are compliant with the surface of the terrain. The flexible gripper can extend all the way to the ground and therefore can also be used to grasp objects.

2.1 Rigid gripper

The very different roles of these two grippers require different features. The rigid gripper must ensure a rigid connection, in order to lift another s-bot. Moreover a strong force is necessary to correct misalignment during connection. The force available to close the rigid gripper of our prototype is 15N. When completely closed, the connection is very firm and the robots can use force sensors to assess the effects of their pulling actions on the other robot. If only partially closed, the rigid gripper allows small movements useful to interactively explore several pulling directions. This feature has been suggested by biologists based on observation of similar behaviors in social insects [1].

To achieve the force of 15N, the actuator of this gripper is a tractor placed inside the main body of the robot, as illustrated in figure 3 (right). The tractor is composed of a slider pulling the cable and slipping over a worm gear with a path of 0.3mm. The worm gear is driven by a motor and three gears with a total reduction of 16. That makes an advance of 0.01875mm/rev

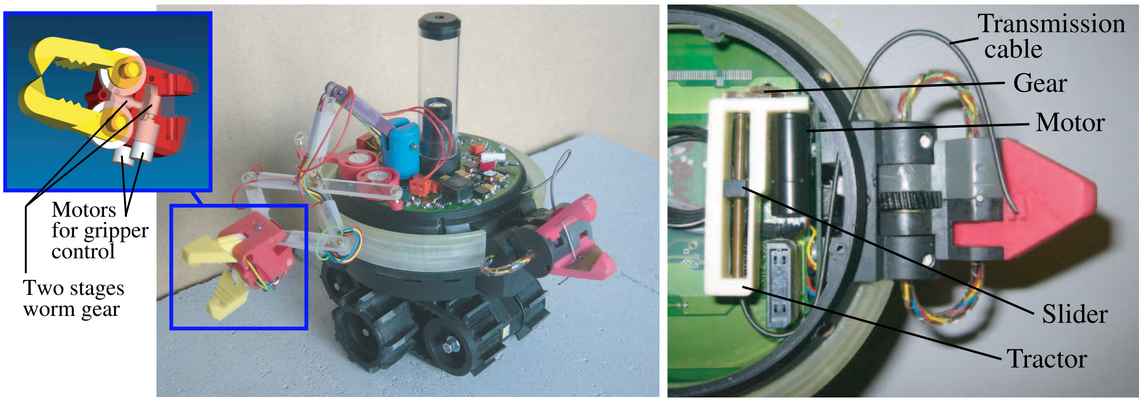

Figure 3: S-bot showing its grippers with the detail on the flexible gripper (left) and detail on the tractor and way cable of the rigid gripper (right).

for the slider. The transmission to the gripper is done by a cable. The opening of the gripper is ensured by a helicoidal spring, placed within the differential mechanism.

The rigid gripper is supported by a mobile structure that can rotate in a range of +90°/-45° around a horizontal axis and has sufficient torque to lift another s-bot.

2.2 Flexible gripper

The flexible gripper is composed of an extensible arm and of a gripping device. The gripper (figure 3) is actuated by two motors in parallel through a two stages worm gear. The whole mechanism is included in the gripper support as illustrated by the CAD view of figure 3. Because of the extreme motor miniaturization, the gripper can exert a force of approximately 1N. However, once the gripper is closed, a non-reversible gear ensures a reliable connection even if the robot is pulling. Errors in alignment are corrected during the grasping procedure by the flexibility of the arm, without need of much force in the gripper itself. The shape of the gripper is similar to the rigid gripper, but it also includes two rows of teeth to grasp various types of objects.

3 Sensors

Both grippers are equipped with two light emitters diodes (LEDs) and a light sensors to detect whether an object has been grasped and to communicate with connected robots. The response of the sensor combined with the activity of the emitters is illustrated in figure 4. These measurements allow to define the position of the ring of another s-bot in the two horizontal directions that are not mechanically limited by the shape of the gripper.

The grasping ring all around the s-bot body also includes the same type of light emitters and receivers as the gripper, but can display RGB colors. This feature allows to communicate in long distance by displaying a color that can be seen by other robots using their onboard camera. When a robot is connected to the ring, the same devices allows local communication inside the swarm-bot structure.

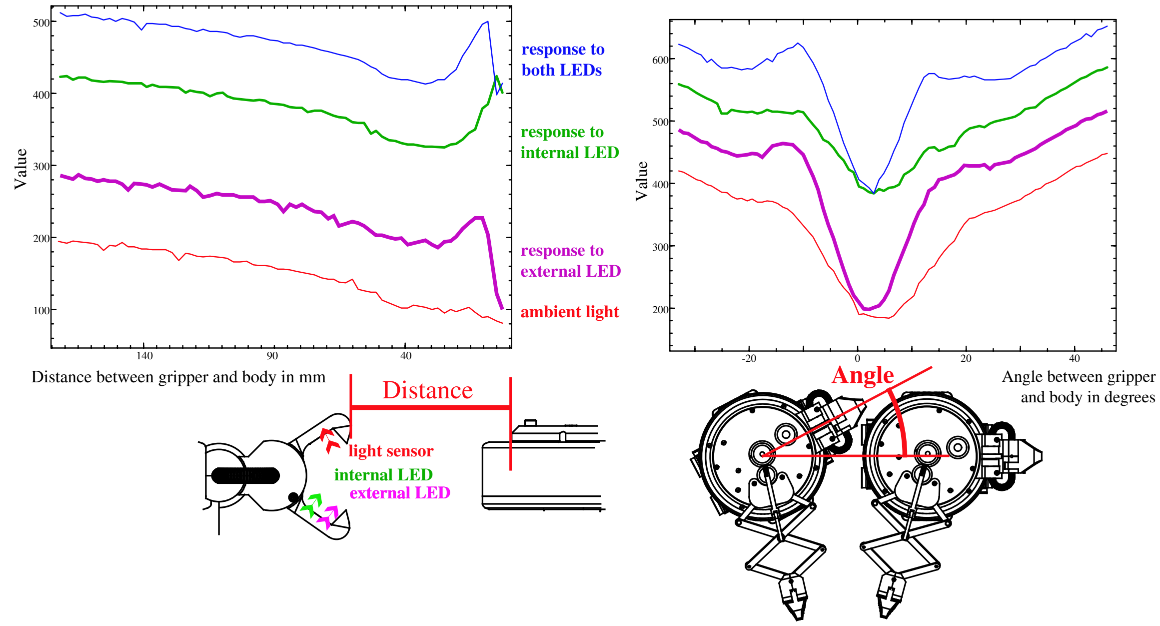

Figure 4: Response of the gripper sensors when approaching another s-bot (left) and when rotating the gripper over another s-bot (right)

4 Behavioral validation

In this section we present two preliminary experiments that validate the swarm-bot connection concept in autonomous control conditions. Both focus only on the fixed gripper functionality and illustrate the use of the sensors, the gripper itself and its elevation in relatively flat surfaces. In the first experiment we show an example of a connecting sequence and *passive use* of the connection to pass over a gap. In the second experiment the gripper elevation movement is actively exploited to pass a step that a single s-bot could not pass. We call this an *active use* of the connection.

4.1 Passive use of the connection: Passing a gap

This first experiment validates the swarm-bot connection concept in real conditions. In particular, it tests the gripper design and the autonomous connection sequence. The goal is to pass over a gap too big for a single s-bot.

Figure 5 (left) shows the control program of each robot as a finite state machine. The first s-bot uses ground proximity sensors to detect the gap, stops and ask for help switching on the color ring. Reacting to the event, the second s-bot approaches and uses the optical barrier of its gripper (figure 4 left) to detect the first s-bot. Once it is sufficiently close, it starts a circular scanning to find the optimal connection position (figure 4 right). When the position is found, the gripper is closed with some vertical oscillations to compensate small misalignments. As soon as a firm connection is established, the two s-bots (now called *swarm-bot*) pass over the gap and disconnect when the second s-bot detects the end of the gap with its rear ground proximity sensor.

Figure 5 (right) presents 6 images of the experiment. The establishment of the connec-

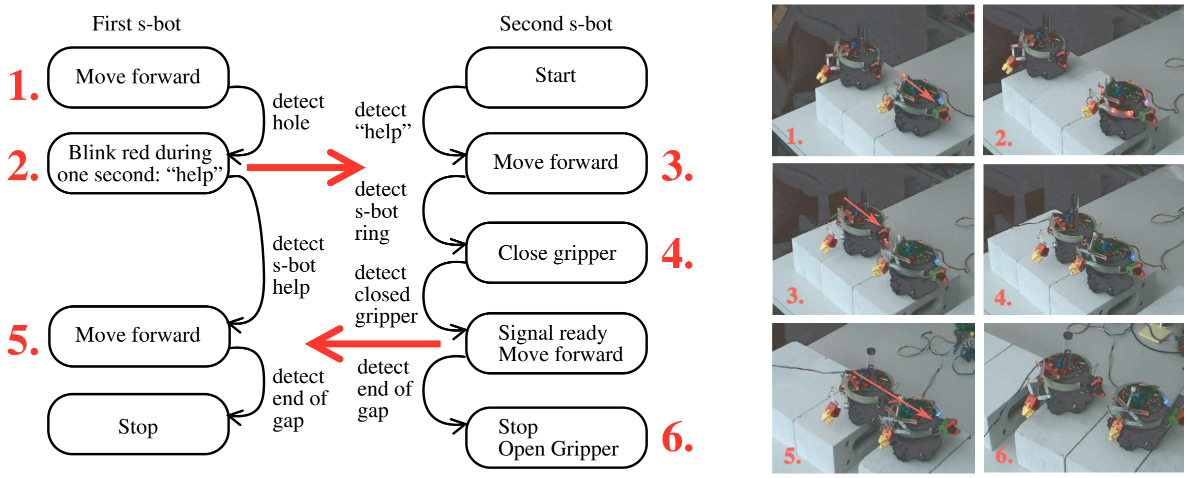

Figure 5: S-bot control for grasping and pass sequence.

tion is one of the most challenging phases. In its current stage of development, an s-bot can successfully establish a connection with the ring of another s-bot only on almost flat terrain. Autonomous connection in rough terrain will require a modification of the control program to include search on the vertical axis as well as better positioning by using the panoramic camera available on the s-bot.

4.2 Active use of the connection: Passing a step

In this experiment the goal is to pass a step too high for a single s-bot. This is possible by actively controlling the elevation of the rigid gripper to lift and lower another s-bot.

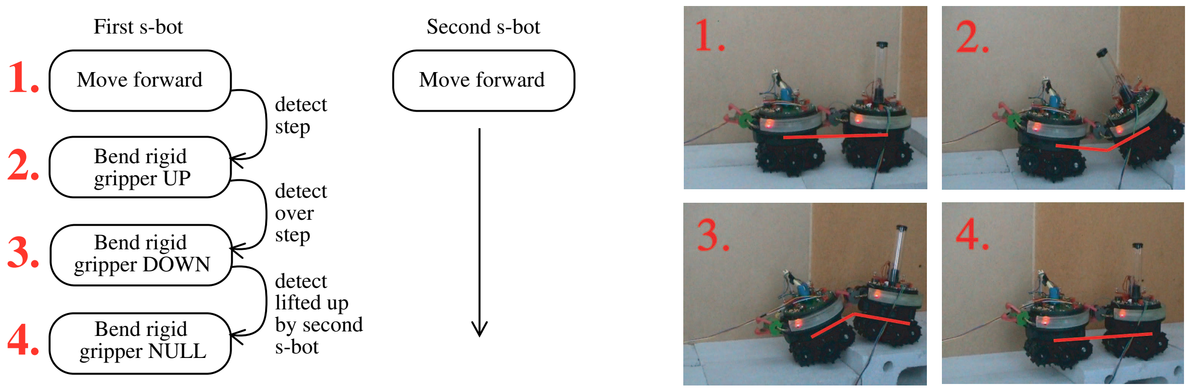

Figure 6: S-bot control for step passing sequence. Notice that here it is the first s-bot (in the direction of motion) that grasps the second s-bot.

Figure 6 (left) describes the control program as a finite state machine. All the work is done by the s-bot in front who is both detecting the step and adjusting the elevation forces on the rigid gripper. Figure 7 shows the values of the ground sensors and of the gripper bending while the s-bot moves over the step. The step is detected by the increasing value of the front inclined ground sensor. At this time the connection is bent up. As consequence the s-bot lifts itself up, the front ground sensor value falls and the front inclined ground sensor value continue to increase. As soon as the edge of the step is reached by the tracks, the front inclined ground sensor value falls. Then the s-bot moves over the step and both ground sensors show a peak corresponding to the edge passing in their field of view. Shortly after, the back sensor detects the edge too. Once the first s-bot has passed the step, the connection is bent down. As a result, all sensor values return to their normal state and the gripper is positioned to the ”null” position.

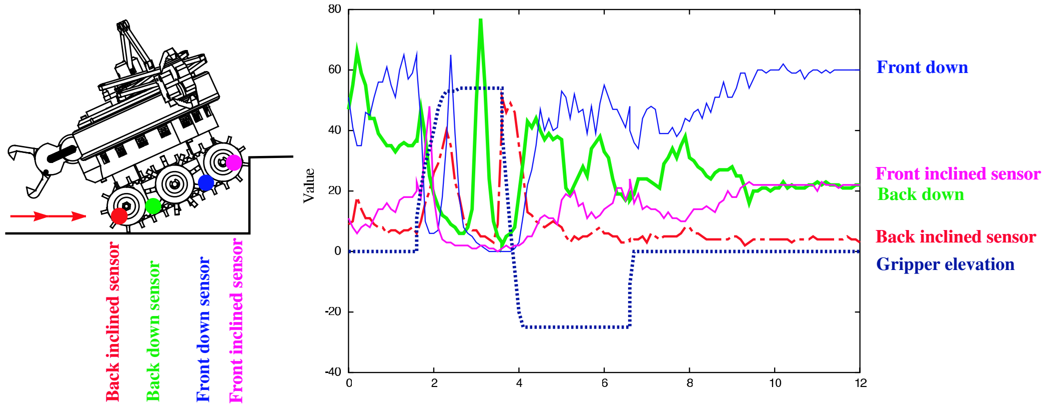

Figure 7: Plot of most important variables of the first robot in the step-passing sequence.

In this case, simple software filters are sufficient to cope with sensor noise. For more complex terrain situations, s-bots are already equipped with pitch and roll sensors that could be used to better interpret sensory data.

5 Conclusion

We described the connection mechanisms and functionalities of the swarm-bot system. This design is very different from existing systems because of the very different constraints of a mobile robot in comparison with a self-reconfigurable system. We also validated the system in two experiments with the autonomous control of a connection sequence and its exploitation in passive and active mode. The mechanical, sensory, and light emitting properties of the s-bot connections make this project unique and very promising for the exploration of new applications of the swarm intelligence paradigm.

This paper focuses on the establishment of connection within short range distance on a nearly flat ground. The methods described here will be enhanced to perform a long range approach and connection in all-terrain conditions. To achieve this goal other sensors of the s-bot will be exploited, such as the omnidirectional camera, the s-bot inclination sensors and the torque sensors included in the gripper and the s-bot body.

In addition to the mentioned efforts, future work will include linear and non-linear swarm-bot configurations with more than two s-bots as well as configurations exploiting the flexible gripper.

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