Superlinear Physical Performances in a SWARM-BOT

Francesco Mondada, Michael Bonani, André Guignard, Stéphane Magnenat,
Christian Studer, and Dario Floreano

Laboratory of Intelligent Systems,
Ecole Polytechnique Fédérale de Lausanne (EPFL),
`http://lis.epfl.ch`, project web page: `http://www.swarm-bots.org`

Abstract. A *swarm-bot* is a robotic entity built of several autonomous mobile robots (called *s-bots*) physically connected together. This form of collective robotics exploits robot interactions both at the behavioral and physical levels. The goal of this paper is to analyze the physical performance of a swarm-bot as function of its size (number n of s-bots composing it). We present three tasks and the corresponding swarm-bot performances. In all three tasks we show superlinear performances in a range of n where the physical forces applied in the structure fit to the robot design. This superlinear performance range helps in understanding which swarm-bot size is optimal for a given task and gives interesting hints for the design of new application-oriented swarm-bots.

1 Introduction

Swarm-bot is a new robotic concept [11] that takes inspiration from insect self-assembling capabilities. For instance some ants use their legs and mandibles to

Fig. 1. A swarm-bot robot composed by six *s-bots* entering a building from a narrow passage (left) and passing a large gap (right).

connect to each other in order to form structures such as bridges or rafts [1]. Similarly, in a swarm-bot the cooperation among single mobile robots (called *s-bots*) is achieved by physical connections [10] (see figure 1). This approach generates new physical properties such as robustness, flexibility and, in some cases, improved physical performances. The **robustness** of this type of distributed system has been well studied in collective robotics [12, 3, 2] and is made possible by the redundancy of the system. The **flexibility** of a swarm-bot is given by its modularity and self-assembling ability. Self-reconfigurable robots show similar properties in their modularity and are also well studied [6, 5].

This paper focuses on the physical **performance** of this new type of self-assembling robotic system. A simplistic way of showing collective performances consist in measuring *threshold performances* on strictly collective[1] tasks, where a single robot cannot solve the problem alone and need the help of other robots to achieve the task. In this type of task the performance can be expressed by the number of robots (threshold m) necessary to solve the task. Even if this threshold does not represent a real quantification of the performances, it is sufficient to demonstrate that the task is strictly collective and to show the ratio between individual and collective performances. Typical examples of strictly collective tasks are object pushing [9] or lifting [4]. In swarm robotics there are similar examples for gap or step passing [11, 10]. It is more difficult but also more interesting to collect *quantitative performances*, both on strictly or loosely collective tasks. This type of measurement can give a better indication of the improvement the collective system brings as function, for instance, of the number of robots used. An interesting characteristic of collective performances is the collective speedup factor [8] of a group of n robots, given by equation 1.

$$CS(n) = \frac{mP(n)}{nP(m)} \tag{1}$$

where $P(n)$ is the performance of a group of n robots and m is the minimal number of robots needed to perform the task. We can distinguish between superlinear performances when $CS(n) > 1$, linear performances when $CS(n) = 1$ and sublinear performances when $CS(n) < 1$. A simple combination of n robots having no influence on each-other should generate a linear performance by performing the task n times better or faster than one robot or module (see for instance gap or step passing with polypod [13]). In most situations it is hard to avoid interferences between the robots, for instance because of a common resource. Those interferences often affect performance and generate sublinear properties (see for instance a simple object clustering using Khepera [7]). In some situations, however, interferences are constructive and help in better solving the task, generating superlinear performances (see the collaboration rate in a stick pulling task [4] or the pushing time for two robots pushing a box [9]). Tasks where we can observe superlinear performances are of course the best application area for collective robotics.

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[1] *Strictly* collective tasks need the collaboration of more than one individual. *Loosely* collective tasks can be solved by one individual having sufficient time [8].

In addition to the characterization of the linearity of the performance, it is important to verify the scalability of this property. It is of course more interesting when these properties scale well to a high number of robots.

This paper focus on swarm-bot performances based on three experiments: Object pulling, gap passing and step passing. The next three sections show that a swarm-bot can solve these task with superlinear performances.

2 Object pulling

2.1 Setup

The goal is to pull an object using a swarm-bot in chain configuration, as illustrated in figure 2 left. To measure the performances of the swarm-bot, the pulling force is measured by a dynamometer connected to the first s-bot. The other s-bots form a chain behind the first one, pulling in the same direction. The robots are remotely controlled by an operator. The pulling force is measured as function of the number of robots.

2.2 Results and discussion

Table 1 shows the average pulling force (over three tests) of swarm-bot of different sizes (n) and on four different ground conditions. The collective speedup $CS(n)$ is given for each ground condition and averaged at the end.

Table 1. Pulling force

Number of s-bots n composing the swarm-bot	1	2	3	4	5
Average pulling force ground 1 $P_1(n)$ [N]	2.65	6.75	11.4	15.1	18.5
$CS_1(n)$	1	1.27	1.43	1.42	1.4
Average pulling force ground 2 $P_2(n)$ [N]	2	8	11	12	17.5
$CS_2(n)$	1	2	1.8	1.5	1.75
Average pulling force ground 3 $P_3(n)$ [N]	3	7.5	12	13.5	15
$CS_3(n)$	1	1.25	1.33	1.12	1
Average pulling force ground 4 $P_4(n)$ [N]	4.7	10	11.6	19.2	23.5
$CS_4(n)$	1	1.06	0.82	1.02	1
Average CS(n)	1	1.4	1.36	1.27	1.29

Table 1 shows that in average a swarm-bot composed by two s-bots displays superlinear performance in respect to a single s-bot. Only on ground number four the performance is nearly linear. In average two robots together perform 1.4 times better than the sum of their individual performances. The collective speedup shows superlinear performances up to five robots, but for $n > 2$ the speedup is less important. The large performance step between one and two s-bots is generated by a physical stabilization of the pulling structure. As shown on the right of figure 2, an s-bot alone cannot generate an optimal pulling force because of the position of the gripper in respect to the tracks and the center of mass, resulting in the s-bot pulling only with the front part of the tracks.

Fig. 2. Left: Chain of five s-bots forming a swarm-bot and pulling on a dynamometer. Right: One s-bot pulling the same dynamometer.

When two s-bots ($n = 2$) build together a swarm-bot structure, they achieve a much better stability. In this structure the center of mass is better placed with respect to the structure and both s-bots can pull with tracks and wheels well placed on the ground. This allows each robot to provide a maximal performance, much better than the performance they would achieve alone. For a swarm-bot composed by more than two s-bots there is no additional structural improvement, which is shown by the decreasing value of $CS(n)$ for $n > 2$. This decreasing collective speedup is also a result of the loss of forces in the chain when $n > 3$, not allowing a proper addition of the individual performances. This loss of performances is due to the connections, the orientation of the robots and the inter-robot efforts. For a larger number of robots ($n > 5$) forces are sufficiently strong to break the chain or even break the gripper of the first robot of the chain. For this reason tests have been made only for $n \leq 5$.

3 Passing a gap

3.1 Setup

In this task the goal is to pass a gap. The swarm-bot configuration is a chain as in the previous experiment (see figure 3) but we exploit here the rigidity of the chain. In this experiment the robots are assembled by hand and controlled by a simple program performing hole detection and robot lifting to compensate structure bending. Depending on the gap size, this is a strictly collaborative task with a threshold performance. We have quantified the performance in respect to the number of s-bot by measuring the maximal gap size the swarm-bot structure can pass. This parameter was introduced by Yim [13] for the polypod performances, under the term of V_d.

Table 2. Gap passing performance

		Number of robots				
		1	2	3	4	5
Polypod earthworm	$P(n) =$ gap V_d [cm]	2.8	5.6	8.4	11.2	14
	$CS(n) = \frac{P(n)}{nP(1)}$	1	1	1	1	1
Swarm-bot	$P(n) =$ gap size [cm]	4	9	18	22	22
	$CS(n) = \frac{P(n)}{nP(1)}$	1	1.125	1.5	1.375	1.1

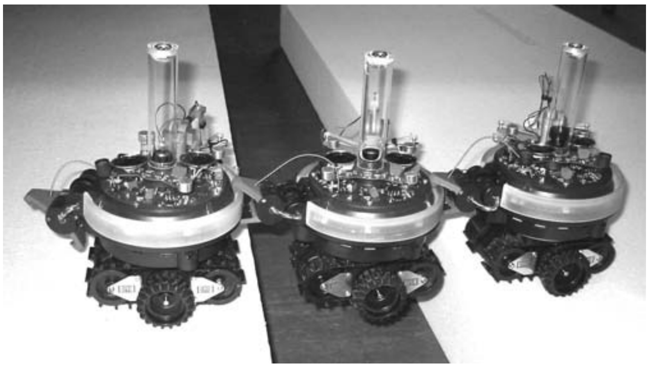

Fig. 3. Three s-bots passing a gap in swarm-bot configuration.

3.2 Results and discussion

Table 2 summarizes the performances given by Yim [13] for the polypod self-reconfigurable robot, the maximal gap size a swarm-bot composed by n s-bots can pass ($P(n)$) and the resulting collective speedups $CS(n)$. For $n \geq 4$ the gap size a swarm-bot can pass can be considered constant, because the gripper cannot support more than two s-bots suspended horizontally. Furthermore, when two s-bots are suspended horizontally, the third robot supporting them has a very strong pressure on the tracks. In the actual version, this pressure can block the tracks and immobilize the s-bot, stopping the whole swarm-bot.

Despite the limitations mentioned above for $n \geq 4$, the measurements show a distinctive collective speedup for n between 3 and 4. The best speedup is obtained for $n = 3$ which is explained by a structural reason, as illustrated in figure 4. When two s-bots self-assemble into a swarm-bot, their structure becomes longer than twice the length of an s-bot because of the length of the connecting device. This extra length is not well exploited for a swarm-bot composed by two s-bots because the center of mass is not placed over a supporting track. With three s-bots the swarm-bot can fully exploit its length because the center of mass is situated over the tracks of the second s-bot in the chain.

Table 2 shows clearly that the collective speedup observed on swarm-bots and on self-reconfigurable robots are very different. For swarm-bots the speedup is superlinear in a short range, corresponding to the limited capabilities of each s-bot[2]. In self-reconfigurable robots the speedup is linear but for a bigger range, corresponding to the bigger structure this type of robots can build.

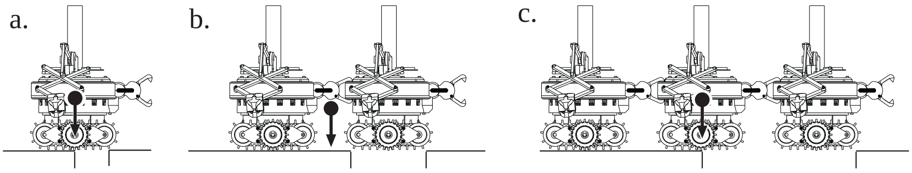

Fig. 4. Center of mass of a swarm-bot facing a gap, depending on the number of s-bot connected. The maximal gap size the swarm-bot can pass depends on the position of the center of mass in respect to the tracks.

4 Passing a step

4.1 Setup

In this task, the goal of the swarm-bot is to pass a step. For a step size bigger than two centimeters this is a strictly collaborative task with a threshold performance, as for the gap passing task. Also in this case we use a chain configuration. A peculiarity of this task is that the swarm-bot must bend properly to pass the step, as illustrated in figure 5. To achieve this task the s-bots have been remotely controlled. We have quantified the performance with respect to the number of s-bots by measuring the maximal step size the swarm-bot can pass. This parameter was introduced by Yim [13] for the Polypod performance, under the term of V_b.

4.2 Results and discussion

Table 3 summarizes the performances given by Yim [13] and those measured on swarm-bots. The number of s-bots has been limited to five because of mechanical constraints: The mechanical effort applied to the connection ring around the robot is very important when bending the swarm-bot structure (see [10] for details). With the actual hardware and for $n > 5$ the ring can broke. Because of this limitation, the step size ($P(n)$) would not increase significantly for $n > 5$.

This task shows impressive results from the point of view of all-terrain navigation. The s-bots can pass a step of their own size, which is a performance only few self-reconfigurable robots such as M-Tran [6] can achieve.

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[2] Each s-bot can lift, with its gripper, only one other s-bot. In self-reconfigurable robots a module can lift several other modules

Table 3. Step passing performance

		Number of robots				
		1	2	3	4	5
Polypod earthworm	$P(n) =$ gap V_b [cm]	2.8	5.6	8.4	11.2	14
	$CS(n) = \frac{P(n)}{nP(1)}$	1	1	1	1	1
Swarm-bot	$P(n) =$ step size [cm]	1.5	4.5	10	14	16
	$CS(n) = \frac{P(n)}{nP(1)}$	1	1.5	2.22	2.33	2.13

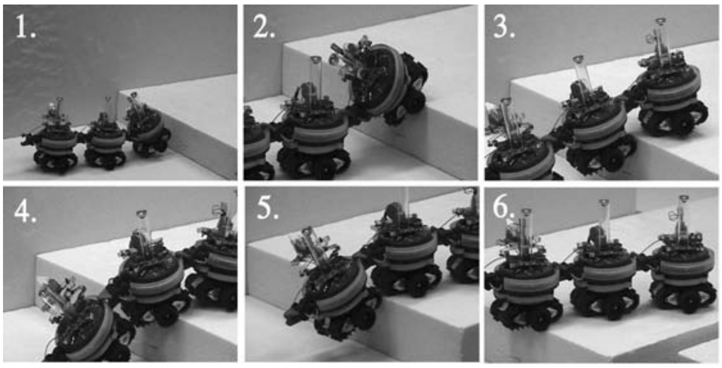

Fig. 5. Sequence of actions a swarm-bot composed by three s-bots must execute to pass a step of 10 cm.

The collective speedup shown in this task is the highest among all experiments that we performed. The larger $CS(n)$ value is obtained for $n = 4$, but superlinear speedups are already obtained for $n = 2$ and continue for $n = 5$. The reasons of this superlinear performance are to be found in the better structural stability of the swarm-bot configuration. A single s-bot, despite its tracks, has a very limited all-terrain navigation capability, due to its relatively high center of mass. This is the reason of the very poor performance of one s-bot in step passing. A swarm-bot configuration made of two s-bots has a much better stability and can deal with a larger variety of terrain conditions. In addition to the stability of the structure, this task exploits the flexibility of the swarm-bot configuration. By bending its structure, the swarm-bot can improve significantly the all-terrain mobility. This is also the main explanation for the large $CS(n)$ value in the case of $n = 3, 4$ and 5. These configurations use more physical links and thus more flexibility in the chain shape, enabling better obstacle passing.

Also in this case the collective speedup shows superlinear performances which are very different from the linear performances shown in self-reconfigurable robots [13]. Even if the superlinearity range ($2 < n < 6$) was bigger than in the previous two experiments, it is smaller than the one observed for linear performances in self-reconfigurable robots (generally $n > 10$).

5 Conclusion

We presented three experiments showing swarm-bot performances as function of the number of s-bots composing it. We can observe two main properties:

1. **Superlinear performance**: All three experiments show superlinear performance. This is a clear indication that the physical connection plays a constructive role in the collaboration between robots. This constructive interaction between s-bots results in performances that are by far bigger than those obtained by the sum of the single robots contributions.
   Most of the superlinear performances generally observed in collective robotics are due to an optimal task distribution. This is not the case of the swarm-bot. In our experiments the superlinearity is due to a mechanical improvement of the system and applies to physical tasks. This is a new phenomenon in collective robotics that deserves further exploration.
2. **Limited scalability**: The scalability of the results is limited to a small range ($2 < n < 5$) in swarm size. This is a clear limitation of our system, but the upper limits are clearly linked to physical and mechanical characteristics of the robot design. This means that the designer of the robot has an influence on these performances. Despite the possibilities of design improvement, physical limitations will always put an upper boundary to the superlinearity of this type of performances.

Although superlinear performances are a well known phenomenon in collective robotics, our experience brings a new element showing these properties in physical tasks using self-assembling capabilities at the robot level. This is a key aspect of our approach and can radically change the way of designing a robotic system for tasks such as all-terrain navigation or object transportation.

Global performance has shown to strongly depend on small design details. The detailed s-bot design choices for all-terrain navigation and inter-robot connection clearly shape the individual and swarm performances. This is a key issue in collective robotics engineering that has already been shown in other projects [4] and is shown here at the level of physical connection. Small implementation details have even more impact on the performance of the collective system if these performances are amplified in a superlinear matter. Our results should be an additional motivation to develop better design techniques to exploit collective speedup from the beginning of the design phase by predicting the performance of the collective system.

Figure 6 summarizes the collective speedup of the three experiments described in this article. We can see that the smallest speedup is obtained by the simplest task (object pulling) where the features of the physical link between the s-bots are less exploited. In this case the link is used only for creating a pulling connection, but does not exploit the rigidity or the mobility of the link. The second task uses the rigidity of the link and gets a better speedup with a maximal

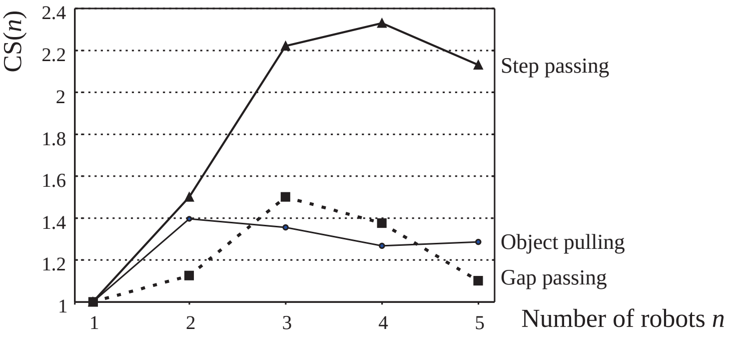

Fig. 6. Summary of the collective speedup as function of the number of s-bots and for each of the three tasks presented in this article.

value for an higher number of robots. The last task, step passing, exploits all the properties of the physical link (rigidity and mobility) and achieves the best collective performances for a higher number of robots. These results demonstrate the relationship between exploitation of the physical link and collective speedup.

Another interesting point to observe is the difference between the performance of a swarm-bot and those of self-reconfigurable robots. Self-reconfigurable robots show nice linear performances mainly due to the simplicity and mechanical strength of their modules, allowing linear addition of the performances [13]. Our design uses as basic building block a fully autonomous individual with more complexity than a self-reconfigurable module, with much more weaknesses and relatively limited capabilities. This choice brings sublinear performances for high numbers of robots ($n > 10$) but superlinear ones for small swarm-bots ($n < 10$).

The experiments described above give an indication of the optimal size of a swarm-bot when addressing physical tasks. For example the performance measured shows that chains of four robots exploit in an optimal way this capability. Therefore the most efficient swarm-bots for all-terrain navigation should have a radius of four s-bots. These indications will be also useful for the design of new swarm-bots designed for specific applications.

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[3] http://lapwww.epfl.ch

ble for any use that might be made of data appearing in this publication. The Swiss participants to the project are supported by the Swiss Government.

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