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A Review of Swarm Robotics: A Different Approach to Service Robot

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***Abstract* -- Swarm robotics is the study of how a large number of relatively simple physically embodied agents can be designed such that a desired collective behavior comes from the local interactions among the agents and between the agents and the environment. Swarm robotics is a new step to the coordination of large numbers of relatively simple robots. The approach takes its inspiration from the system-level functioning of social insects which demonstrate three desired characteristics for multi-robot systems: robustness, flexibility and scalability. Service robotics, as it has been intended so far, focuses on the accomplishment of a service mission mainly as the result of the action of a single robot. Swarm robotics tackles very same problem from a different stance, i.e., as the result of a team effort or team work of simple units. The demand for autonomous operation and mobility of each robot has led to the development of connectivity. Some of the solutions employed for this problem are inspired upon physical connectivity of social insects.**

***Keywords* – Swarm, S-bot, Social insects, Service robot, Multi-robot system**

I. INTRODUCTION

Swarm robotics is a novel approach to the coordination of large numbers of robots and has emerged as the application of swarm intelligence to multi-robot systems [1]. Different from other swarm intelligence studies, swarm robotics puts emphases on the physical embodiment of individuals and realistic interactions among the individuals and between the individuals and the environment. Swarm robotics represents a novel approach to the coordination of large numbers of robots whose main inspirations stem from the observation of social insects. These insects, such as ants, wasps and termites, are known to coordinate their behaviours to accomplish tasks that are beyond the capabilities of a single individual; ants can carry large preys to their nest, termites can build large mounds from mud within which a desired level of temperature and moisture is maintained. The emergence of such synchronized behaviour at the system-level is rather impressive for researchers working on multi-robot systems, since it emerges despite the individuals being relatively so incapable, despite the lack of centralized coordination and despite the simplicity of interactions.

"Swarm robotics is the study of how a large number of relatively simple physically embodied agents can be designed such that a desired collective behavior emerges from the local interactions among the agents and between the agents and the environment." [1]. Swarm robotics is a new approach to the coordination of large numbers of relatively simple robots. The approach takes its inspiration from the system-level functioning of social insects which demonstrate three desired characteristics for multi-robot systems: robustness, flexibility and scalability. Robustness can be defined as the degree to which a system can still function in the presence of partial failures or other abnormal conditions. Social insects are highly robust. Their self-organized systems can still work even after losing lots of system components or changing the environment parameters considerably.

Flexibility can be defined as the capability to adapt to new, different, or changing requirements of the environment. Flexibility and robustness have partly conflicting definitions. The difference between two occurs in problem level. The biological systems have this level of flexibility and can easily switch their behaviors when problems change. For instance, ants are so flexible that they can solve foraging, prey retrieval and chain formation problems with the same base self-organized mechanism. Scalability can be defined as the ability to expand a self-organized mechanism to support larger or smaller numbers of individuals without impacting performance considerably. Although there is a range in which the swarm performs in acceptable performance levels, this range is proffered to be as large as possible.

A *swarm-bot [2]* 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.* 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, provides an additional dimension to collective robotics where interactions among robots are often virtual or take place through pushing actions. Service robotics, as it is widely performed today, usually assumes a given service to be carried out by a single robot or, at most, by a small group of them working together.

II. SYSTEM-LEVEL PROPERTIES

The system-level operation [1] of a swarm robotic system should exhibit three functional properties that are observed in natural swarms and remain as desirable properties of multi-robot systems.

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A. FLEXIBILITY:

The individuals of a swarm should be able to coordinate their behaviors to tackle tasks of different nature. For instance, the individuals in an ant colony can collectively find the shortest path to a food source or carry a large prey through the utilization of different coordination strategies.

B. ROBUSTNESS:

The swarm robotic system should be able to operate despite disturbances from the environment or the malfunction of its individuals. A number of factors can be observed in social insects behind the robustness of their operation.

C. SCALABILITY

The swarm should be able to operate under a wide range of group sizes and support large number of individuals without impacting performance considerably. That is, the coordination mechanisms and strategies to be developed for swarm robotic systems should ensure that the operation of the swarm under varying swarm sizes.

III. DISTINGUISHING CHARECTERISTICS

First, the research should be relevant to the coordination of a swarm of robots. That is, the individuals should have a physical embodiment, be situated, and be able to physically interact with their environment. Moreover, the coordination mechanisms being studied should promise to be scalable for a wide range of swarm sizes. Second, the robotic system being studied should be rather homogeneous. That is, the individuals that make up the swarm should be rather identical, at least at the level of interactions. Coordination strategies developed for heterogeneous multi-robot systems, which consist of individuals that differ in their interactions due to their physical embodiment or their behavioral control, fall outside of the swarm robotics approach. Third, the individuals should be relatively simple. The simplicity criterion in the definition does not directly refer to the hardware and software complexity of the robots, but rather meant to emphasize the limitations in their individual capabilities relative to the task. The members of the swarm system should be relatively incapable or inefficient on their own with respect to the task at hand. That is, either

(i) The task should be hard or impossible to be carried out by a single robot, and the cooperation of a group of robots should be essential, or

(ii) The deployment of a group of robots should improve the performance/robustness of the handling of the task. Fourth, the individuals should have local interaction abilities. This constraint ensures that the coordination between the robots is distributed, and that it is more likely to scale with the size of the swarm. Mechanisms that rely on global interaction capabilities is likely to be bounded by the bandwidth and the range of communication channel and may create unscalable coordination mechanisms.

A. BUILDING OF ROBOT:

One major research direction has been the development of physical swarm robotic systems since the building of a swarm robotic system takes more than gathering a number of copies of a generic robot platform. All the studies towards this end have focused on developing mobile robots that are aimed to provide a research platform and not intended for real-world operation. Below we will discuss the extra requirements expected from robots that would be used in swarm robotic systems.

Sensing and Signaling: The main emphasis in swarm robotics is the interaction among the robots as well as the interaction of the robots with their environment, resulting in extra constraints for the robots to be used.

Communication: Unlike stand-alone robotic systems, communication by plugging cables to the robots is no longer a feasible option. Therefore the robots have to support wireless communication (i) between a console and the robots, to allow easier monitoring and debugging of algorithms on individual robots, (ii) among robots such as in the form of ad-hoc networks.

Physical interaction: The robots should be able to physically interact with each other and the environment since self-assembly or self-organized construction is interesting topics for research.

Power: The robots should have a long battery life. In most studies, the swarm may need to operate for a period that is long enough for the collective behavior to emerge, and the goal to be reached.

Cost: The robots should be as cheap as possible, since, unlike stand-alone robots, they will be sold at least in groups of tens.

Size: Size does matter in swarm robotic systems. The robots should be small enough not to increase the size of test arena when experimenting with the system, and yet big enough not to limit the expandability of the robot or increase the cost of the swarm robots due to miniaturization in components.

Simulation: The swarm robotic systems require realistic simulators which would be essential to speed up development of new control algorithms. Such simulators need to model the interactions between the robots as well as the interactions of the robots with their environment in a realistic way that is also verified against the physical robots.

B. ALGORITHMS FOR SWORM ROBOTICS

A variety of algorithms [3] have been implemented to be run on swarms of robots. Some provide basic functionality, such as dispersion, while others demonstrate seemingly complex teamwork, such as chain formation. Although the algorithms all produce different emergent behavior, they all have many features in common. These features derive from the basic goals of swarm robotics discussed earlier and include:

Simple and elegant i.e. the robot controller that dictates the behavior of the individual robots is very simple. The behaviors of the individual robots can usually be represented as a state machine with few states and edges.

Scalable i.e. swarm robotics algorithms are designed so that they work for any number of robots. Also, they are expected to scale well as new robots are added.

Decentralized i.e. the robots in a swarm are autonomous and do not follow any exterior commands. Although a member of a swarm can be directly and predictably influenced by the behavior of another, the choice is under its own accord. Being decentralized is often coupled with being scalable.

*Usage of local interactions i.e. l*ocal interactions are used over broadcasting messages in the majority of these algorithms. Even broadcasts are implemented as message-hopping protocols. This ideal is a major factor in the scalability of the system

IV. MECHANICAL CONCEPT AND IMPLEMENTAION

In SWARM-BOTS, [2] 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 1 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 fl*exible gripper*. The two grippers play very different roles in swarm-bot configurations. The rigid gripper allows creating 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.

A. 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.

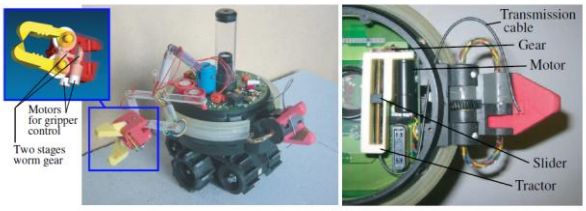

Fig.1 - S-bot showing its grippers with the detail on the rigid gripper (left) and detail on the tractor and way cable of the rigid gripper (right).

C.FLEXIBLE GRIPPER

The flexible gripper is composed of an extensible arm and of a gripping device. The gripper (fig.2) 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 fig.2. 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.

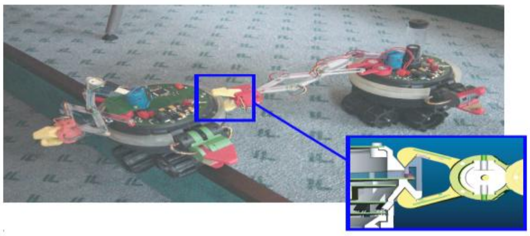

Fig.2 - Two s-bots connected by mean of the flexible gripper with detail on matching between gripper and grasping ring.

D.SENSORS

Both grippers are equipped with two light emitter's diodes (LEDs) and 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 emitter. These measurements allow defining 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 communicating 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 allow local communication inside the swarm-bot structure.

E. CONTROL

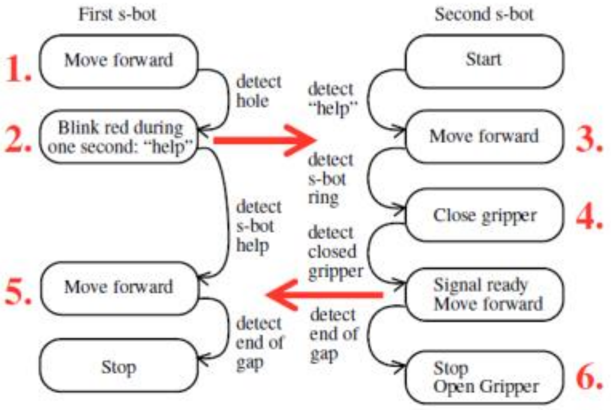

Fig.3: S-bot control for grasping and pass sequence

Fig.3 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 (Fig.3) to detect the first s-bot. Once it is sufficiently close, it starts a circular scanning to find the optimal connection position (Fig.4). 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.

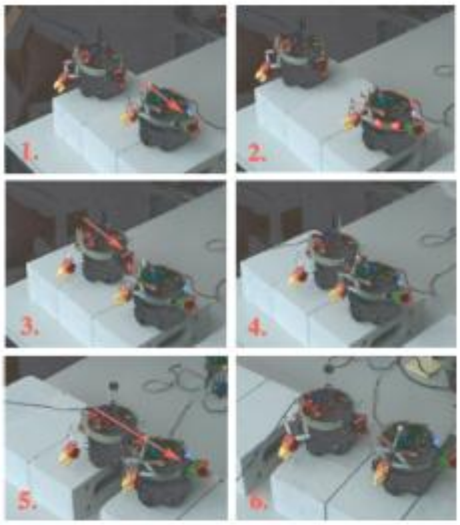

Figure-4: S-bot control for grasping and pass sequence.

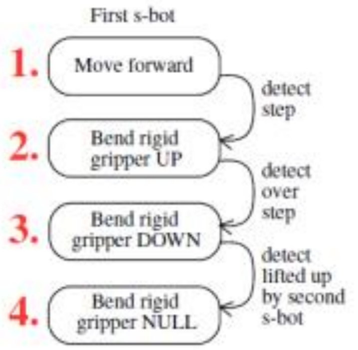

Fig.5: S-bot control for step passing sequence.

Fig.5 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 6 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.

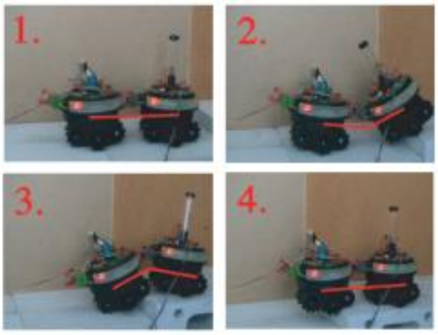

Fig.6: S-bot control for step passing sequence.

V.ADVANTAGES AND DISADVANTAGES

A. ADVANTAGES

Robotic swarms [3] have several advantages over their more complex individual robot counterparts and are the results of using many robots instead of just one. This is made possible by the simple design of the robot modules because they are often less expensive and easier to build. When comparing the capabilities of a robot swarm to the capabilities of an individual robot, it is best to view the swarm as an individual entity performing complex behaviors at the macro-level.

1. The first improvement is an obvious one: robot swarms are able to cover more area than an individual robot. This is analogous to distributed search algorithms that are able to cover different parts of a search space at once.

2. The second improvement over individual robots is swarm robots are fault tolerant because the swarm robotics algorithms do not require robots to depend on one another. If a single module fails, the rest of the swarm can continue performing its actions as if that module never existed. Meanwhile, an individual robot system may become worthless if there is a failure in a critical component. This type of robustness is an extremely important feature in complex or hostile environments.

3. Another feature of robot swarms is their effectiveness scales well with the number of members. Adding more robots is all that has to be done to increase the effectiveness of a swarm.

4. The algorithms for swarms scale well and do not depend on the number of robots. On the other hand, it is not always clear how to improve the effectiveness of an individual robot system. Often time's improvements in hardware require additional software upgrades, which is not the case with swarms. These properties make multi-robot systems suitable for several application domains.

B. DISADVANTAGES

Although swarm robotics research [3] is still relatively new and has not produced a swarm that has been used in a practical application, several have been proposed in the literature. One algorithm deals with the common robot task of mapping an environment. A swarm of robots could disperse in an environment and cover different locations at once.. Foraging is a general behavior that can be used for search and rescue (or destroy), mining, food gathering, organizing, etc. Patrolling has several security applications such as detecting intruders, guarding borders, etc. None of these domains have been reported as being solved by robot swarms. Below we will describe some of the problems that have been addressed in swarm robotics research and describe some of the exemplary studies addressing them.

Aggregation: Self-organized aggregation, the grouping of individuals of a swarm into a cluster without using any environmental clues, is a common behavior observed in organisms ranging from bacteria to social insects and mammals

Dispersion: Self-organized dispersion can be considered as the opposite of aggregation and is of interest in surveillance scenarios.

Foraging: This problem is inspired from the behavior of ants which search for food sources distributed around their nest. In this problem, the challenge is to find the optimum search strategies that maximize the ratio of returned food to the resources committed (such as the number of individuals doing foraging or signaling strategies) in an environment

Self-assembly: This behavior is observed in ants, where they form chains through connecting to each other to build bridges or float-like structures to stay above water. The problem of self-assembly can be defined as the self-organized creation of structures through the formation of physical connections among a swarm of individual robots.

Connected movement: This problem can be described as follows: How can a swarm of mobile robots, physically connected to each other, coordinate their movement such that the group moves smoothly in an environment and avoids environmental obstacle, such as holes, in a coordinated way. The robots, which are physically connected to each other through their grippers, were able to sense the forces acting on their bodies through traction sensors and were able to feel holes underneath them.

Cooperative transport: Ants are known to transport large preys to their nest through coordinating their pushing and pulling actions. Such coordination ability is obviously valuable for swarm robotic systems since it allows individuals to join forces generating a combined force large enough to pull a heavy object. This problem is partially related to the connected movement, with the difference that it includes a passive object that needs to be transported.

Pattern formation: This is a rather generic term for the problem of how a desired geometrical pattern can be obtained and maintained by a swarm of robots without any centralized coordination. The problem can be categorized into two; namely geometric and functional pattern formation.

Self-organized construction: This problem can be formulated as follows: How can number of passive objects, randomly distributed in an environment, and it is clustered together by a swarm of robots. This problem, sometimes also being referred as "aggregation" has been one of first problems studied.

V. CONCLUSION

Swarm-bots, because of their extreme plasticity, can find interesting applications anywhere it is required a high degree of physical adaptation and a low level of human intervention or monitoring. Tasks which fall in this category might be space exploration of harsh and humanly dangerous environments, assembly of space modules, handling of dangerous materials, mining, and even "harvesting" material or goods from a physically constrained location. Given such a multi-purpose nature, swarm-bots might also find further applications in the future which are currently even not foreseen.

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