Quantitative information in sematectonic stigmergy for swarm robots

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Abstract

This paper considers the benefits of transferring quantitative information represented by changes of their environment between members of a robot swarm. This form of communication is an example of sematectonic stigmergy, a type of indirect communication. The work has been partially inspired by colonies of weaver ants and their nest building task. It is conjectured that even if members of a swarm are not directly aware of the other swarm members, they can still cooperate with each other. They can do this by gaining information via changes of their working environment, which are caused by other members. This kind of information transfer is called sematectonic stigmergy. Another important aspect of sematectonic stigmergy investigated in this project is the transfer of multi-level information, which is very helpful for many possible swarm robotic tasks. The ideas developed in this paper are confirmed by a series of physical experiment with W-AntBots (Weaver Ant Bots).

1 Introduction

Recently, swarm robots have been studied quite intensively because of the advantages of their cooperation in tasks where one robot or multiple independent single robots are not as effective. To achieve cooperation in swarm robots, communication between members plays a crucial role.

Communication methods in swarm robots can be categorized into 2 main types: direct and indirect. Robots employing the first type are often equipped with wireless communication modules or light emitter/detector systems so that they are able to directly transfer information between each other. However, to implement, this method of communication requires that 2 robots must be within reception range/line of sight of each other at the same time. Moreover, this kind of communication must add to the cost, control complexity as well as the error probability due to cross-talk which will all increase with an increase in the number of robots.

Alternatively, with indirect communication, or stigmergy, robots "send" information to other members of the swarm via their environment. In this way, a receiving robot can still gather information from a transmitting robot after a time delay, and the requirement regarding the proximity of the two robots is removed. This feature gives robots more flexibility in cooperative work.

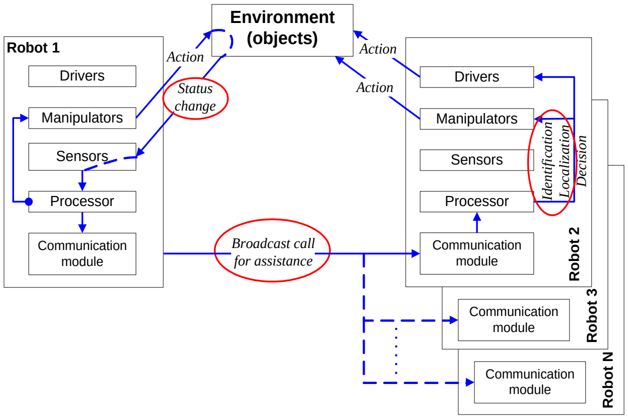

Fig.1: Information flow in direct communication

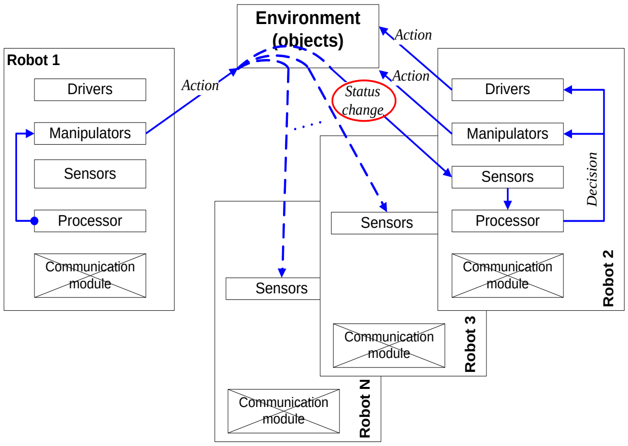

Fig.2: Information flow in indirect communication (stigmergy)

To better illustrate the differences between these two communication methods, it is useful to look at how information flows through out the whole robot-environment system in a process starting from the action of robot 1 to the responding action of robot 2 (fig, 1 and fig.2). In the case of direct communication, the information flow encounters high risk with 3 different points, where errors can be introduced (marked with ellipses) due to: inaccuracy of sensor readings; of communication channel and errors in object identification and team mate localization algorithms. Whereas, for the indirect communication method; errors of the information flow can occur only if the sensors of robot 2 work incorrectly. The information robots transfer to each other is independent of transreceiving devices or processors. Especially, this method does not require robot 2 to identify the object and localize robot 1 – the actions which increase the complexity and cause the highest probability of errors of the working process.

Error propagation is another disadvantage of the direct communication method. An error occurring in sensor readings of robot 1 will then be broadcasted to all other robots and make negative impacts on their decisions. However, this problem can be avoided in the indirect communication swarm, where every robot directly perceives information from the environment. And it is more likely that at least one robot will sense correctly. Together with low cost and simple structure, these are the reasons why indirect communication - stigmergy is seen as a valuable method of communication for research into swarm robots.

Stigmergy methods has been studied and developed successfully for quite a large number of projects. However, most of them focus on using chemical trails, or heat trails as media to transfer a message from one robot to other robots [Purnamadjaja and Russell, 2006; Purnamadjaja and Russell, 2004; Fujisawa et al, 2008; Garnier et al, 2007; Sugawara et al, 2004; Borzello and Merkle, 2005]. This type of communication is called sign-based stigmergy, and is inspired by many real tasks undertaken by social insects.

There is another type of indirect communication method, also found in the biological world, which is called sematectonic stigmergy [Wilson, 1982]. This can be defined as “indirect communication via changes of the environment or objects, caused by other members”. In this way, every robot can get the most direct information of the object it is working with and of the status of the task it needs to complete without being aware of other members of the swarm or processing any other information. Although having many potential applications for swarm robot tasks, this type of communication is rarely mentioned in recent research. The most relevant study using this method is the stick-pulling robot experiments [Ijspeert et al, 2001]. However, in that application, every robot in the group is only able to discriminate two states of the sticks: lifted or not lifted. The robots are not capable of determining differences in the height that the sticks are lifted or of making use of this additional information.

In this paper, we consider robots that can perceive and process multiple-level information from their environment. Based on the multi-level information the robot can make comparisons and decide where it should work in order to produce the best result. The design of the experiments performed in this work was inspired by the nest building task of weaver ants, which cooperatively curl natural leaves to make a nest. In the experiments a group of W-AntBots simulated a part of the weaver ants’ task.

The ability to make comparative value judgements would also be useful for swarm robots performing many other tasks, where the number of possible states of objects is more than two such as box-pushing, pulling, clustering, sorting tasks, etc. For instance, in a box-pushing task, where each box can only be moved by the combined effort of at least 3 robots. We imagine the case when 3 robots are pushing boxes as follows: box A is being pushed by 1 robot, the box B by 2 robots. If the 4th robot comes to help the robot pushing the box A, then the whole group must wait for at least one more robot in order to be able to succeed in moving a box. However, if the 4th robot is able to judge the situation and choose to come to help the group pushing box C, then that box will be moved immediately and all of them can return and help the robot pushing box A. It is obvious that with the ability to make comparisons the whole job can be completed more quickly and more effectively.

This paper is organized as follows. Section 2 provides information about stigmergy methods observed in social insects. This is based on the nest building activities of weaver ants with emphasis on comparative information in sematectonic stigmergy. The following section gives a detailed description of W-AntBots and the experimental environment. Next, the experiment results are presented and discussed in section 4. Finally, Section 5 outlines conclusions and proposals for future work.

2 Sematectonic stigmergy and social insects

2.1 Weaver ants and their special task

Fig.3: Weaver ants folding a leaf to build a nest. (Reproduced by permission of Zainal Halim-Reuter Photographer)

The weaver ant task is known as a great example of cooperative work in the biological world. This is the nest building activities of weaver ants (genus: *Oecophylla*) that form a nest by folding and sticking leaves together. The task is described by Sudd in 1963 [Wilson, 1982] as follows: Firstly all of the ants spread over the leaf’s surface and individually pull up any edge they can grasp.

On a normal leaf, the tip often can be bent more easily than other parts because of rib distribution. When a few ants have successfully bent a leaf onto itself other workers nearby join the effort. After some time, all of ants, who have tried to pull up the harder edges would give up and gather together to the tip and roll up successfully the leaf.

From the point of view of this project the most interesting issue in this task is the way ants cooperate and communicate with each other to finish the job. However, to the best of our knowledge there is no documentation, describing details of the communication mechanism used in this task. There are at least three possible mechanisms that the weaver ants could be using to decide where to apply their efforts in the leaf curling task:

- Direct communication: by contacting their antennae to transfer information, by transmitting and receiving stridulation through the air, by executing a head-waggle pattern or body jerking, etc.
- Indirect communication: by sensing the concentration or identity of a particular pheromone, produced by other ants which are making good progress with the leaf curl task.
- Or by monitoring the change of status of the leaf edge, an ant can decide where it should apply its efforts.

Although the first hypothesis is quite likely, it will not be considered further because it is a type of direct communication, and this project is about indirect communication. The last 2 types of indirect communication are discussed in more detail in the next part of this section.

2.2 Sematectonic stigmergy

Both of the methods of indirect communication mentioned above can be termed “stigmergy”. For a long time biologists have been aware of the use of stigmergy by social insects. It has been seen in ant colonies, bee swarms, wasp swarms, ghost crabs and some other insects. However the terminology stigmergy is still an arguable concept for robotics. In robotics there are many definitions of this terminology [Ricci et al, 2007; Tummolini and Castelfranchi, 2007; Dylan and Maja, 2004]. Generally it can be described as indirect communication among members of a group via their working environment. It is not surprising that this method is well developed and useful for social insects because unlike human beings, they do not have sophisticated languages to communicate directly with each other. Broadly there are two types of stigmergy: sign-based and sematectonic stigmergy.

In relation to the hypotheses about communication in the weaver ant task presented earlier in this section: the second hypothesis is categorized as sign-based stigmergy. The name sign-based is inspired by the way ants or bees leave pheromone trails as a sign to pass information to other members of the colony. The final hypothesis is an example of “sematectonic stigmergy”. The terminology “sematectonic” is a combination of two Latin words: “sema” – sign and “tectonic” – craftsmen [Wilson, 1982]. It means communication among group members via changes of status (shape, position, etc.) of the working environment or objects in the environment, caused by other members.

A project which is very relevant to this study has been reported by A.J. Ijspeert, A. Martinoli et al. and concerns stick-pulling robot experiments [Ijspeert et al, 2001]. In these experiments they studied collaboration between members of a group of robots and investigated models for predicting the behaviour of the whole group based on the work of Kristina Lerman [Lerman, 2004]. Though they did not mention anything about indirect communication in their papers, their experiments still made use of sematectonic stigmergy. In the stick-pulling exercise every robot can understand the change of object status only as a binary value. That is the stick is being pulled up or not. In this project we investigate the case where the number of possible object statuses is bigger than two. This raises a question for a robot that arrives to help with the task: which status is better? Or other words: which robot has achieved better performance and which robot should be assisted to get the best result?

It is proposed that at the start of the weaver ant task all of the available ants try to curl the leaf at random points along the leaf edge. Some parts of the leaf will be easier to curl compared to others. However, eventually they gather at the most promising location which is usually the tip of the leaf. In order to select the most promising location it is proposed that ants which are not making much progress come to help the ants which are having better success in bending the leaf edge.

This hypothesis about weaver ants became the inspiration for this work to investigate the applicability of quantitative information in sematectonic stigmergy among swarm robots. Being able to make value judgements about the information it receives, a robot can compare the performance of other robots. Based on this, it can make useful decisions.

2.3 Decision making algorithm

It is proposed that the way weaver ants work in the nest building task can be described by the following simple algorithm:

```
1. Scan the whole environment (the whole leaf)
2. Determine the biggest change of the object (the
   most curled edge).
3. If there is no significant change (all edges are
   essentially flat)
      Then try a randomly selected point on the edge.
   Else
      Go to the place where the biggest change
   occurred (the most curled edge) and help there.
4. At the chosen edge point the ant tries to lift up the
   edge for a certain amount of time.
5. If the leaf edge is not raised significantly in that
   interval of time
      Then it gives up and starts from step 1.
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This is the algorithm which was programmed into the W-AntBots in our experiments. In terms of logic, this algorithm looks similar to the working algorithm of the Khepera robots in stick-pulling experiments, produced by Ijspeert, Martinoli et al 2001. However, the difference between them lies in step 2 and step 3. While the Khepera stick-pulling robots are only concerned if the stick is being lifted up or not, our robots must make an important comparison about object statuses in order to decide the best location to provide assistance.

Although this algorithm is quite simple, it provides a robust means for the whole colony of ant robots to complete the task. With this algorithm, it is believed that after a certain time, the whole colony will gather together at the best part of the leaf (usually the tip).

To simulate and study the leaf-curling process of weaver ants in a robotics context is the goal of our current project. In the first stage of this project, a series of experiment were implemented to prove the ability of robots to read and compare the different status of objects in their environment. This stage covers the first 4 steps in the algorithm presented earlier. The experimental setup and results of experiments are given in the next section of this paper.

3 Experiments

3.1 W-AntBot

For this project the W-AntBots must have enough abilities to complete the task described above and at the same time they must be as simple as possible (one important requirement for any swarm robot). The structure of the W-AntBot is illustrated in Fig.4:

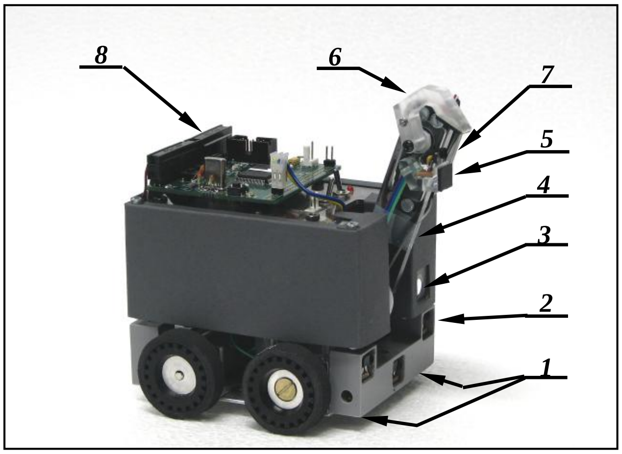


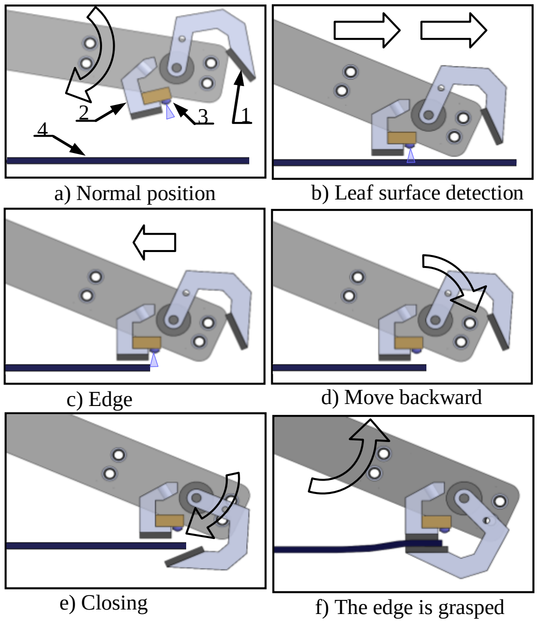
Fig. 4: The W-AntBot
1. Floor presence detecting sensors (3 in front & 3 at back)
2. Obstacle detecting sensors (2 in front & 2 at back)
3. Line-scan sensor
4. Arm, 5. Fixed finger, 6. Active finger.
7. Finger sensor, 8. Microprocessor.

The drive system of the W-AntBots consists of 2 DC motors, one powers the rear right wheel, and another actuates the front left wheel (the other 2 wheels are passive). With these driven wheels the robots can move forward, backward, turn right or left around their center. Control feedback signals are provided by 2 encoders, one on each motor.

To perceive their working environment, every W-AntBot is equipped with 10 infra-red sensors placed at the front and rear of the robot. They help the robot to detect obstacles when moving and to avoid falling off the leaf. The most important sensor of every W-AntBot for this experiment is the line-scan sensor (which plays the role of a "technical eye" to allow the robot to "see" how high the leaf edge is being lifted). This is a sensor array consisting of 128x1 photo diodes to read illumination of 128 pixels in a column. It produces an analog data output, whose voltage levels correspond to the light intensity at each pixel. This sensor is highly sensitive to ambient light sources. To get sharp images of objects, the sensor was placed in a closed tube with a lens. (Fig. 4, pos. 3)

The robot can hold and lift up the leaf by using its manipulator. This is a 2 DOF gripper, constructed as an arm with 2 fingers. One finger is fixed to the arm while the other can rotate around its axis to grasp edges of the leaf. The fixed finger carries an infra-red sensor, which allows the robot to detect and grasp the leaf's edge. All steps of this process are illustrated on Fig.5. Beside that, movements of the arm and the active finger are monitored by built-in infra-red based force sensors.

To control the whole system, an M16C microprocessor from Renesas Technology was chosen. The block-schema of the W-AntBot's system is shown in the Fig.6 .



a) Normal position
b) Leaf surface detection
c) Edge
d) Move backward
e) Closing
f) The edge is grasped

Fig. 5: Edge detecting and grasping process
1. Active finger, 2. Fixed finger,
3. Finger sensor 4. Rubber leaf

Because the main purpose of this project is to investigate indirect communication the W-AntBot is not equipped with any wireless, infra-red or similar communication devices.

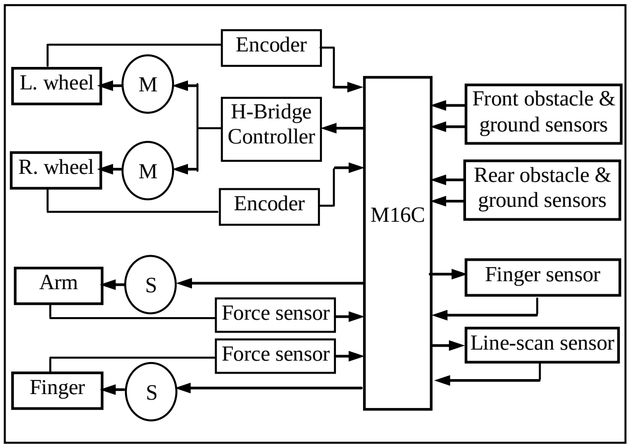


Fig. 6: Block-schema of W-AntBot control system.

3.2 Experimental setup

It is obvious that the W-AntBot cannot work on any natural leaf because of its size. Thus, in the laboratory, an artificial leaf was created. The leaf was required to have some similar characters of a natural leaf, which are: flexible, relatively light compared to the weight of the robot, having a hard direction (difficult to curl) and a soft direction (easy to curl). The artificial leaf was made from 1.5mm thick neoprene rubber because of its suitable elasticity and density. The test leaf has an actual size of 90cm x 120cm, which is suitable for a group of up to 6 W-AntBots to work on it (Fig. 7). On the bottom surface, a series of strips of flexible metal were attached in parallel to the short side of the leaf. In this way, the 2 long edges of the leaf are stiffened.

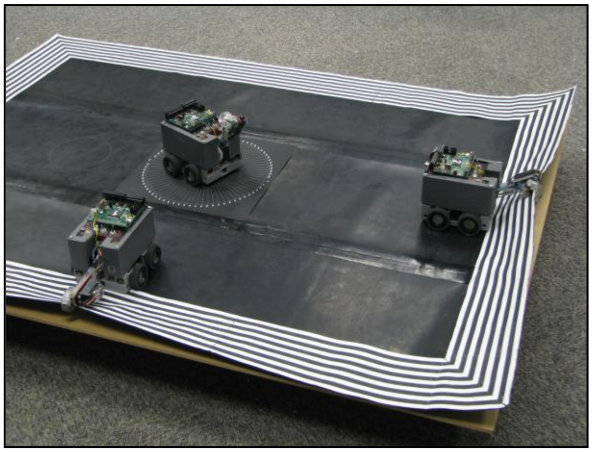


Fig 7: The experimental setup:
Three W-AntBots are trying to fold a rubber leaf.

To help the robots read the height of the leaf edge, the simplest option is to paint the whole leaf a colour, contrast to the ground and surrounding environment. In this case, the length of the leaf in the resulting image is directly proportional to the height of the leaf edge. However, the results of this method strongly depend on the distance from the robot to the leaf edge. A simple method was applied to solve this problem: a number of black and white stripes were stuck on the leaf edge proximity. With this modification, the number of white stripes which a robot can see is proportional to the height of the current edge. Therefore, the dependence of the reading result on the distance is substantially reduced (Fig. 8).

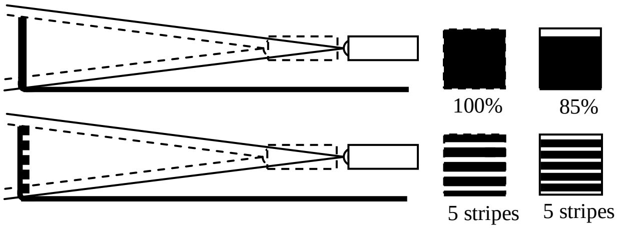


Fig.8: Distance independence solution.
Above: without stripes. Bottom: with stripes.
Right figures: images, read by camera in corresponding cases.

The key feature of this experiment is “indirect communication” among members of the swarm. Members can not send or receive any information directly to each other. However, every robot can “indirectly perceive” other members via their performance, or more exactly, via their influence on the working environment. In this particular case, the working environment is the leaf, and the changes of environment are the height of the leaf’s edges, pulled up by others.

This first stage of the project investigates the ability of the robots to compare information gathered from different parts of the working environment and the way that this information can be used to guide the behaviour of every robot in the group. Three different sets of experiments with these W-AntBots were implemented.

The purpose of the first set of experiments is to examine how the first robot will act with a new leaf, which has not been touched by any other robots. The first robot was started from the middle of a totally flat leaf. The experiment was repeated a number of times and the location, chosen by the robot to attempt to curl the leaf was recorded. If the robots were functioning correctly this first robot would try randomly spaced points along the leaf edge.

In the next group of experiments, a first robot was already lifting an edge of the leaf, the second robot was required to scan from the middle of the leaf, assess the scene and decide where it should move to work. The expected result is that the robot should select a place near the first robot in order to help it in lifting the edge.

The third set of experiments is the most interesting and important because it involves a third robot that must compare and make a correct decision to help a better performing robot. The situation is as follows: after a simultaneous start, the first 2 robots were lifting 2 different parts of the leaf edge. One of the robots is lifting higher than another one; or in other words, one is achieving a better performance than the other. The expected destination of the third robot should be the area around the more successful robot.

The search algorithm used by the robots for this set of experiments is detailed in the flow chart shown in Fig. 9.

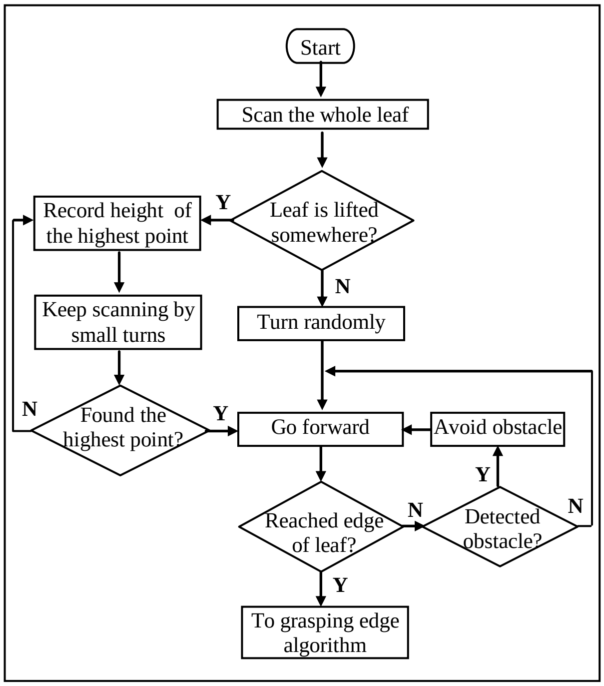


Fig. 9: Promising edge searching algorithm.

After deciding in which direction to go, the robot moves straight forwards. For this reason the moving direction of the robot has the same meaning as its exact destination position for our research purposes. To determine the angle selected by each robot a circle was placed in the middle of the test leaf, calibrated with heading angle. The 0, 90, 180 and 270 degree points of this circle were lined up with the middle points of each edge of the rectangular leaf. In particular, the 0 and 180 degree points direct to the middle of the “soft” edges.

3.2 Experiment results and discussion

Each set of experiments consisted of 40 trials. The trial results are shown on the 3 radar charts below (Figs. 10-12). The moving direction of the robot in each trial is plotted as a sector on the radar chart, and the radius of that plot is proportional to the number of times the robot chooses the associated sector. The angular range of every sector is 5 degree.

It is clear from the first chart (Fig.10) that the distribution of the first robot’s destinations is evenly spread around the leaf. Most of destinations (sectors) were chosen only once by the robot. Only 3 sectors were visited 2 times and there were 2 others with 3 repeats.

This result confirms that the robot could not collect any distinctive information from any point of the environment, and hence it had to choose randomly where to try.

However, in the second set of experiments (Fig.11), in which the first robot was pulling up the edge of the leaf higher than it was elsewhere, it can be seen that all destinations of the second robot now clearly gather around the side of the leaf, where the first robot was lifting. The largest number of destinations for the second robot was found just next to the position of the first robot. This result showed that the 2nd robot successfully gained information from the working environment and based on that it correctly chose where it should apply its efforts to the best advantage. In this case it did not directly sense the 1st robot.

The results of the 3rd set of experiments are given in Fig.12. These results demonstrate how a robot can make a decision in a multi-change situation. In this experiment, the leaf was being lifted at 2 points: 0° and 90° by the 2 robots. However, the first robot at the 0° point was achieving more success than the 2nd one at 90°. As a result the edge at 0° was lifted higher than that at 90°. The task of the 3rd robot was to decide which robot it should come to help. After 40 trials, the recorded results show that the 3rd robot approached a position within 10° of the 1st robot 11 times and this is substantially higher than any other place (angle). Moreover, the total number of times when the 3rd robot came to a position within ±30° around the 1st robot has found to be 95% of the trials (38 out of 40). There were only 2 times, when the 3rd robot came to help the 2nd robot. From this result, it is clear that the 3rd robot “preferred” to help the 1st robot, which was the more successful one. It means that the 3rd robot made a good choice in a collaborative working environment.

This result has successfully proven that without being able to detect each other and without any direct communication, the robots still can choose a beneficial course of action by accessing information from environment changes.

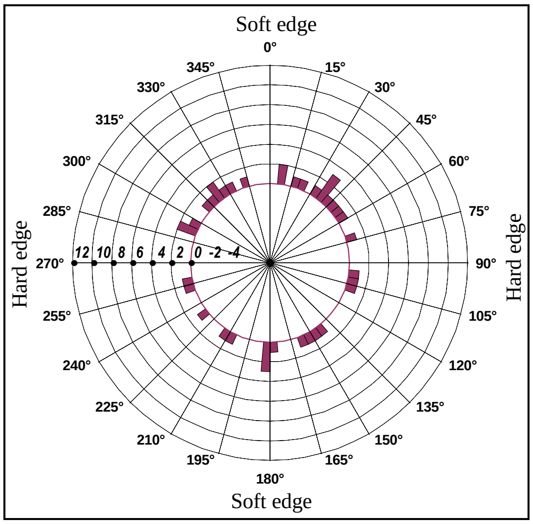


Fig.10 Distribution of robot's destination in the 1st case: There is no other robots working on the scene

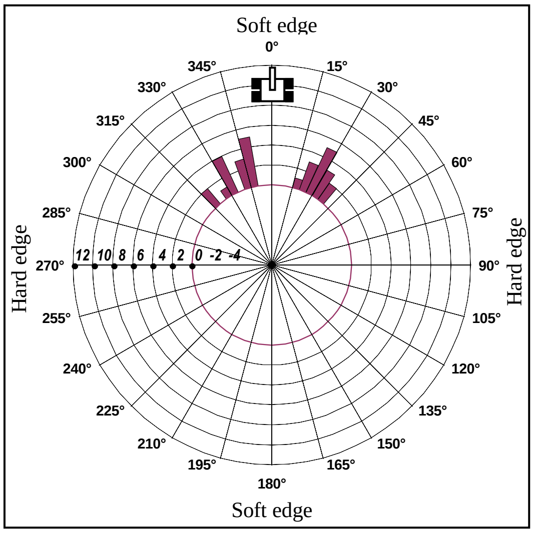


Fig.11 Distribution of the 2nd robot's destination when The 1st robot is lifting at 0deg position.

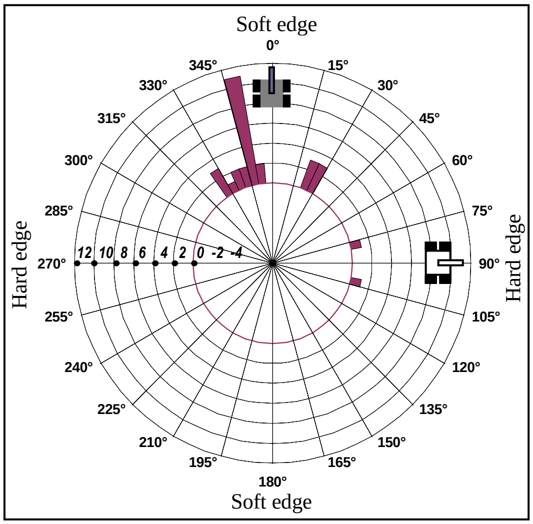
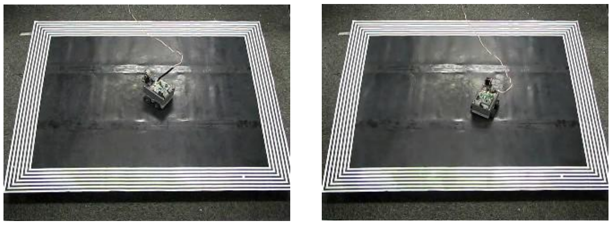


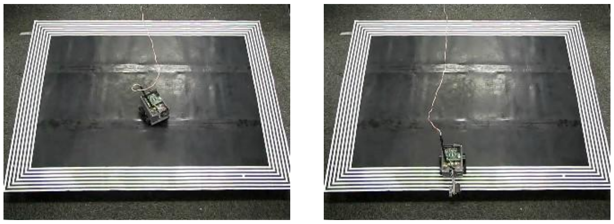
Fig. 12 Distribution of the 3rd robot's destination when The 1st robot is lifting higher at 0deg position. The 2nd robot is lifting lower at 90deg position.

Some of photos, captured from trials of these sets of experiments are shown on Figures 13-15. Due to the high power consumption of the robot circuitry, external power cords were used instead of battery to extend the working endurance of the robots. The "hard" edges of the experimental leaf are parallel to the horizontal edges of the images.



a) Scan around

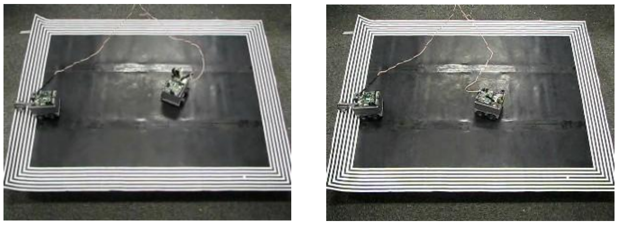
b) Scan around



c) Scan around

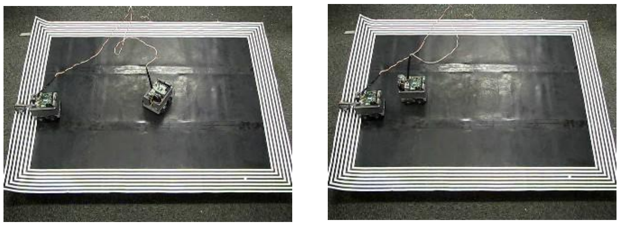
d) Grasp a random edge

Fig. 13 The 1st case: There is no other robots working on the scene.



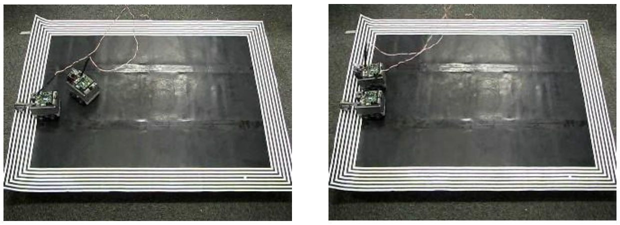
a) Scan around

b) Scan around



c) Scan around

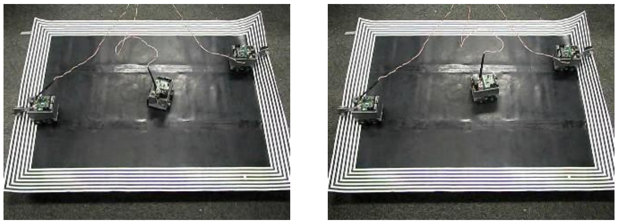
d) Determine the better edge



e) Avoid collision

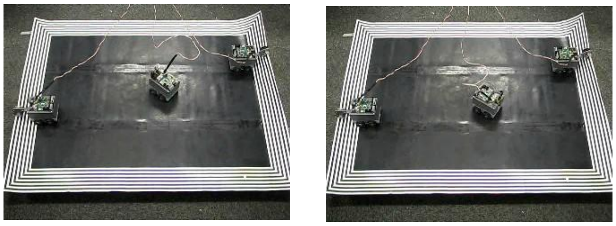
f) Grasp the chosen edge

Fig. 14 The 2nd case: One robot is lifing one edge.



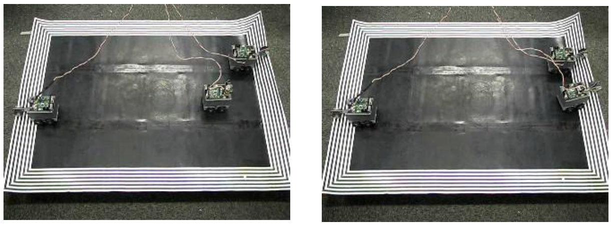
a) Scan around

b) Scan around



c) Scan around

d) Scan around



e) Determine the better edge

f) Grasp the chosen edge

Fig. 15 The 3rd case: The robot on the right side is lifting higher than the robot on the left side.

4 Conclusion and future work

This paper has investigated a new form of robot communication which involves "quantitative information in sematectonic stigmergy". Even if every robot in a swarm has no ability to communicate and transfer information directly, they can coordinate their actions by observing changes in their environment. Physical experiments with W-AntBots verified that swarm robots can not only gather binary information from their environment, they can also distinguish multi-level information, which can be useful for decision making processes involving value judgements.

These experiments will form a good basis for the next steps of the project. In the near future experiments will be carried out to complete the weaver ant task of finding the point where the leaf is most compliant and then folding it with a group of 6 W-AntBots. To avoid negative impacts of local decisions of the robots; or in other words, to guarantee that the whole leaf to be fully explored, a "time-varied randomness" will be applied to the working algorithm of all W-AntBots. After completing that stage, we would like to investigate 2 important factors of sematectonic stigmergy for swarm robotics: time taken to complete the task and probability of task success. These factors will depend on group size and working environment size. After that, the same experiments will be implemented but with some form of direct communication on each robot. It is strongly believed that in many situations, sematectonic stigmergy will have advantages over direct communication.

Reference

[Wilson, 1982] Edward O. Wilson 1982, 'Communication: Basic Principles', in Sociobiology – the new synthesis, The Belknap Press of Harvard University Press, Cambridge, Massachusetts, and London, England.

[Purnamadjaja and Russell, 2006] Purnamadjaja, A.H., Russell, R.A., 'Robotic Pheromones: Using Temperature Modulation in Tin Oxide Gas Sensor to Differentiate Swarm's Behaviours', Proceedings: ICARCV '06. 9th International Conference on Control, Automation, Robotics and Vision, Singapore, pp. 1 - 6 .

[Purnamadjaja and Russell, 2004] Purnamadjaja, A.H., Russell, R.A., **'**Pheromone communication: implementation of necrophoric bee behaviour in a robot swarm'**,** Proceedings: 2004 IEEE Conference on Robotics, Automation and Mechatronics, Singapore, vol. 2, pp. 638 – 643.

[Fujisawa et al, 2008] Fujisawa, R., Imamura, H., Hashimoto, T., Matsuno, F., **'**Communication using pheromone field for multiple robots'**,** Proceedings: IEEE/RSJ International Conference on Intelligent Robots and Systems, 2008, Nice, France, pp. 1391-1396

[Garnier et al, 2007] Garnier, S., Tache, F., Combe, M., Grimal, A., Theraulaz, G., **'**Alice in Pheromone Land: An Experimental Setup for the Study of Ant-like Robots', Proceedings: 2007 Swarm Intelligence Symposium, IEEE, Honolulu, Hawaii, pp. 37-44

[Sugawara et al, 2004] Sugawara, K., Kazama, T., Watanabe, T**., '**Foraging behavior of interacting robots with virtual pheromone', Proceedings: 2004 International Conference on Intelligent Robots and Systems, Sendai , Japan, vol. 3, pp. 3074-3079

[Borzello and Merkle, 2005] Borzello, E., Merkle, L.D., 'Multi-agent cooperation using the ant algorithm with variable pheromone placement', Proceedings: The 2005 Congress on Evolutionary Computation, Edinburgh, UK., vol.2, pp. 1232-1237

[Ricci et al, 2007] A. Ricci, A. Omicini, M. Viroli, L. Gardelli, and E. Oliva, "Cognitive stigmergy: towards a framework based on agents and artifacts," in Environments for Multi-Agent Systems vol. III, D. Weyns, H. V. D. Parunak, and F. Michel, Eds. Berlin: Springer-Verlag, 2007, pp. 124–140.

[Ricci et al, 2005] A. Ricci, M. Viroli, and A. Omicini, "Environment-based coordination through coordination artifacts," in Environments for Multi-Agent Systems, D. Weyns, H. V. D. Parunak, and F. Michel, Eds. Berlin: Springer-Verlag, 2005, pp. 190-214,.

[Tummolini and Castelfranchi, 2007] L. Tummolini and C. Castelfranchi, "Trace signals: the meanings of stigmergy," in Environments for Multi-Agent Systems vol. III, D. Weyns, H. V. D. Parunak, and F. Michel, Eds. Berlin: Springer-Verlag, 2007, pp. 141-156.

[Dylan and Maja, 2004] Dylan, Sh. & Maja, M., 'On the use of the term 'Stigmergy'', USC Robotics Research Labs, 2004, viewed on 12th March 2009, http://robotics.usc.edu/ ~dshell/stigmergy.html

[Ijspeert et al, 2001] Ijspeert, A.J. , Martinoli, A. , Billard, A. , Gambardella, L. M.,'Collaboration through the Exploitation of Local Interactions in Autonomous Collective Robotics: The Stick Pulling Experiment', Autonomous Robots, vol. 11, num. 2, 2001, p. 149-171.

[Lerman, 2004] Lerman, K., "A model of adaptation in collaborative multi-agent systems," Adaptive Behavior 12(3–4):187–198, 2004