Congregation Behaviour in a Robot Swarm Using Pheromone Communication

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Abstract

Characteristically, social insects are extremely reliant on their use of pheromones to maintain their social activities as a colony unit. This paper describes an on-going project to investigate the possibility of using pheromone communication in a robot swarm. The particular example of pheromone communication considered here was inspired by the queen bee pheromone. This pheromone is only emitted by a queen bee and has a major influence on the colony. One of its main functions is to attract and stabilize the other members of the colony. In robotic systems, one of the proposed applications for this behaviour is to allow swarm members to locate and recognize a robot leader that releases the appropriate pheromone signal. The robot pheromone is also used to direct grouping behaviour in the robots. This paper provides details of the swarm robots used in the project, their sensors and the simple reactive control algorithm that was developed to mimic the insect response to the queen bee pheromone. Results of practical experiments are also described.

1 Introduction

Pheromone communication is an important new area of study in robotics. Pheromones are chemical signals used by organisms to communicate between members of the same species [Price, 1997; Wyatt, 2003]. In the insect world, pheromone communication is widely used for coordinating colony activities including aggregation, food gathering, broadcasting an alarm and defence, reproduction and recognition of conspecifics [Michener and Duncan, 1974; Kerkut and Gilbert, 1985].

Pheromone communication could offer a number of advantages that may be of benefit in robotic systems. First, the broadcast pheromone signals particularly can be used in conditions where electromagnetic or optical signalling is not unusable or advisable, such as for clandestine tasks or in structures containing a large proportion of metal. This form of communication also indicates the presence of and traces out an unobstructed path between the source and recipient . However, it does not guarantee that the robot will be able to negotiate the path.. In addition, this signal does not require clear line-of-sight between the sender and receiver compared to a visual signal. Finally, the range and persistence of a pheromone signal can be tailored by appropriate choice of chemical and its concentration whereas other signals only act at the time they are produced [Agosta, 1992; Wyatt, 2003]

Because of the advantages of pheromone communication, several projects have been undertaken that aim to implement it on robotic systems. Odour localization is the most significant aspect of pheromone communication, and this has been investigated by a number of robotics researchers. Research on robotic odour localization started with projects that considered an individual robot [Rozas *et al*., 1991; Russell *et al*., 1995; Ishida *et al*., 1996; Atema, 1996; Kazadi *et al*., 2000; Lilienthal *et al*., 2003; Russell, 2004] to group of robots [Genovese *et al*., 1992; Sandini *et al*., 1993; Hayes *et al*., 2002]. Most of these investigations were limited to odour localization, and further developments such as pheromone or chemical communication among robots were not considered. Recently, simulation studies [Kawamura and Ohuchi, 2000] and consideration of virtual pheromone [Payton *et al*., 2001] have been used by some researches in order to implement pheromone communication. However, very few robotic researchers have used actual chemical pheromones in their experiments. Some examples of the use of real robotic pheromones are the chemical trail laid by a robot for other robots to follow [Russell, 1995] and the rescue of disabled robots that release a pheromone in a robot swarm [Purnamadjaja and Russell, 2004]. The rescue of disabled robots was our previous experiment in pheromone communication robotics.

This project has developed another example of pheromone communication in a robot swarm. It was inspired by aspects of communication via the queen bee pheromone. A queen bee releases pheromone throughout a colony to stimulate different actions in the colony. One of the actions is to keep the bee swarm in the colony. This can also be used as a form of kin recognition. The presence of the pheromone stabilizes the colony. In the absence of the queen, the performance of the colony declines significantly [Agosta, 1992]. Many aspects of this behaviour can be implemented in robotic systems. A robot leader could broadcast specific chemicals as distress calls to command different actions or activities. As previously mentioned, this type of communication could be used in a situation where communication using radio or light beacons is not possible or desirable. In this implementation, the robot leader releases a chemical and its function is to gather the robots into a group. This is congregation behaviour in a robot swarm using pheromone communication.

In order to implement this congregation behaviour, there are several problems that must be addressed. Firstly, the robot leader should be able to carry and broadcast a chemical plume to indicate its position. The other robots must then be able to locate the robot leader; therefore, a robust odour localization algorithm will be required. After locating the robot leader, robots should be able to congregate. In the absence of the chemical, the swarm robots will start to search for the chemical plume again.

The rest of this paper is organized as follows. The experimental equipment and robot algorithm are described in Sections 2 and 3. Experimental results are then provided in Section 4. Finally, conclusions and future work are outlined in Section 5.

2 Experiment Set Up

2.1 Robots and Their Sensors

In this experiment, the robots are similar to those used in the previous project concerning bee necrophoric behaviour [Purnamadjaja and Russell, 2004]. Several modifications were made to the robots to suit the need of the current application.

The dimensions of the robots are 13 cm high and 24 cm diameter. A tin oxide gas sensor type TGS2600 manufactured by Figaro Engineering Inc. is mounted on each robot for detecting the chemical plume. Besides this, each robot has three whisker sensors for avoiding collisions. The robots are controlled by a stand-alone program stored in flash memory of an on-board Infineon C167CR microcontroller. Figure 1 shows a photograph of one of the mobile robots.

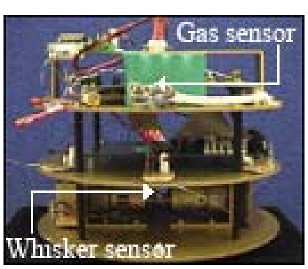

Figure 1. A mobile robot equipped with an odour sensor and three whisker sensors.

The robot leader requires the capability of carrying and releasing chemicals. The chemical plumes created by the robot leader must be effective until congregation achieved and therefore, an appropriate chemicals handling and broadcasting system had to be developed for this experiment. A chemical bubbler system [Pearce *et al.*, 2003] consisting of a small electric pump and chemical containers was chosen to generate chemicals vapour by bubbling air through a liquid chemical. The controlled electric pump can pump air at a rate of 1 litre per minute. The bubbler produced a stream of air carrying the chemical vapour. To disperse the chemical vapour more widely, air from the bubbler was introduced to the intake of a small 5V electric fan producing airflow of 1.49 litres per second. The pump, containers, and fan were attached to the robot leader (Figure 2). They are light enough that they do not affect the robot leader mobility.

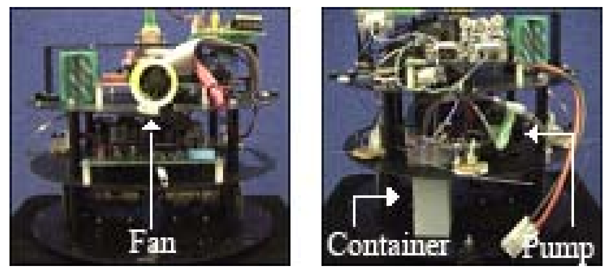

Figure 2. The robot leader carrying a pump, chemical container and fan.

The chemical containers are detailed in Figure 3. The system has been designed to carry two different chemicals. Release of each chemical is controlled by a separate solenoid valve constructed from a modified relay. The air is supplied to each container via an input non-return valve. On the outlet side a modified relay operates a valve that controls which chemical is released by the robot. In this experiment, we only used a single pheromone chemical. That chemical was methylated spirits; a mixture of ethyl alcohol (95%) and methyl alcohol (5%).

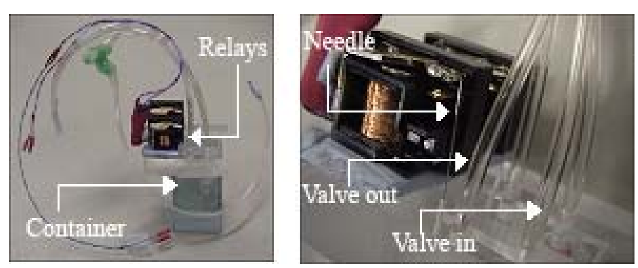

Figure 3. The chemical container.

2.2 Arena

The experimental arena measured 252.7 cm x 345.8 cm and was sufficient to accommodate 4 robots. The arena layout is shown in Figure 4. Experiments were conducted in an indoor environment with very minor ambient air movement. The only significant airflow was produced by the small 5V electric fan carried by the robot leader.

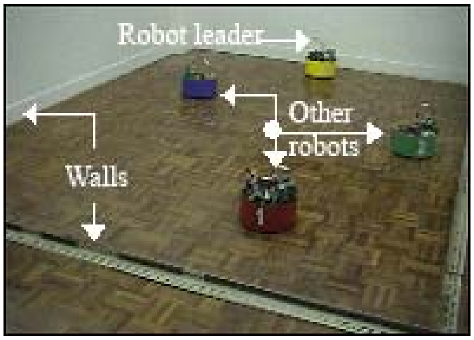

Figure 4. The experimental arena.

For each experiment, the robot leader was placed near the walls to maximize the spread of the chemical plume. Initially the other robots were placed randomly at the different positions inside the arena.

2.3 Odour Distribution

In order to help develop the robot control algorithms it was necessary to observe the characteristics of the chemical plume in terms of variability and range inside the experimental arena.

The tin oxide gas sensor mounted on each robot was used to determine the methylated spirits concentration. A 2-dimensional map of chemical distribution was created by recording chemical concentration at a grid of 77 points in a 159.6 cm x 266 cm area. The robot leader was placed at the centre point (0, 0). It then released the chemical for 6 minutes. The peak concentration at each of the 77 points was then measured. Figure 5 shows the resulting contour plot of the chemical concentration inside the experimental arena. The brighter areas denote lower concentration of chemical and the darker areas denote higher concentration. It can be seen that the plume extends well away from the robot leader. There was considerable fluctuation of the concentration measured at each point.

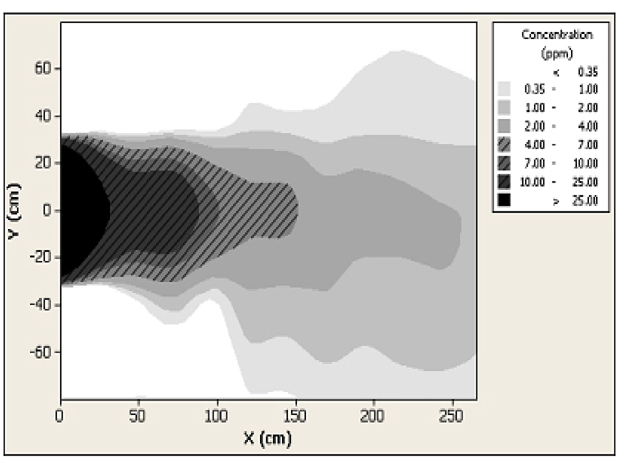

Figure 5. The chemical plume distribution.

3 Control Algorithm

The control code was written in C and uses RTX166 that is a multitasking real-time operating system for C16x/ST10 family of microcontrollers. The program implements a set of functions that provide simple access to the robot's sensors and motors. These functions perform the operations of cleansing the chemical sensor, searching to find the robot leader, avoiding obstacles and congregating.

The cleansing process is an initial process undertaken before the start of each experiment for stabilising the tin oxide gas sensor.

During the searching mode, each robot senses the chemical concentration. As mentioned earlier, rapid concentration changes occur when the sensors are placed in the vapour flow. It was decided that the robot would take one reading every second for 20 seconds to gather a temporal snapshot of the plume. There are several ways to analyse the fluctuating information from the odour plume. These methods include averaging the odour concentration readings, taking the highest reading and taking the difference between highest and lowest readings of odour concentration. An experiment was conducted to decide the best method for this project. A robot was placed inside the chemical plume. The robot moved forward towards the robot leader and after every 10 cm step it would take 20 readings of chemical concentration. This process was repeated until it reached the robot leader. The data were then processed to determine the highest concentration, averaged concentration, and the difference between the highest and lowest concentration. These quantities were calculated and plotted for each point as can be seen in Figure 6. To provide a useful information the graphics should show increasing values with each movement towards the robot leader (X = 0 cm). Dots represent errors where the plotted quantity shows a decreasing value as the robot moves towards the source. It can be seen from the graph that the most reliable method involves taking the highest reading of 20 concentrations.

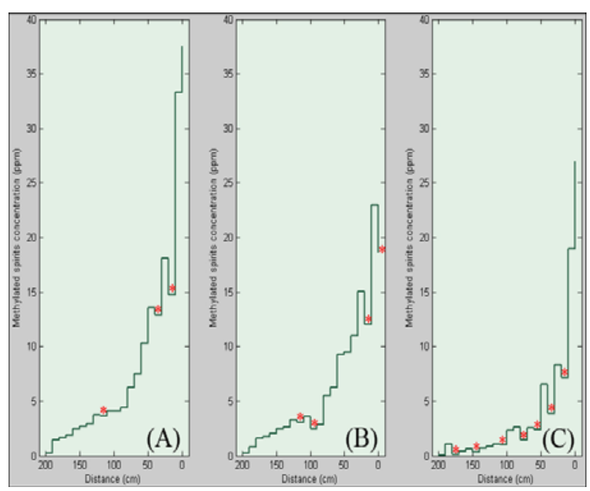

Figure 6. The chemical readings: (A) highest concentration (B) averaged concentration (C) difference between highest and lowest concentration.

Therefore, each robot moves forwards in steps of 21 cm with a speed 0.18 s/cm when searching. After each movement, the robot senses chemical concentration by taking readings in the 20 seconds interval and the highest reading is selected. This procedure helps to overcome the rapidly fluctuating nature of the chemical concentration.

Based on the slow response of the tin oxide gas sensor, the rapid chemical changes inside the chemical plume and the absence of airflow measurement in this experiment; the searching algorithm developed in the previous experiment [Purnamadjaja and Russell, 2004] has been adopted for this project also. However, the arena in this experiment is larger than the arena used in the necrophoric behaviour experiments and there is a plume created by the robot leader. For these reasons the original search algorithm was modified.

In general, the algorithm compares the current chemical reading with the previous reading measured before the last robot movement. The robot search behaviour consists of three main parts.

- When the chemical concentration increased both in low or high concentration conditions, $c_{n+1} \geq c_n$; or when the chemical concentration decreased in a fresh air condition, $c_{n+1} < c_n$ and $c_n < 0.29$ ppm, the robot moved forward as illustrated in Figure 7(A).
- When the chemical concentration decreased in a low concentration condition, $c_{n+1} < c_n$ and 0.29 ppm $< c_n < 0.35$ ppm, the robot started to search ahead moving to three points in a counter clockwise sequence as shown in Figure 7(B). The robot recorded the maximum concentration that it measured at the three positions (c_{n+2}, c_{n+3} and c_{n+4}). It then moved to the highest concentration point (n+2 in Figure 7(B)). In this example the chemical concentration at point n+1 became c_n and the point n+2 becomes c_{n+1}. The algorithm was then repeated.
- When the chemical concentration decreased in a high concentration condition, $c_{n+1} < c_n$ and $c_n > 0.35$ ppm, the robot rotated 180 degrees before performing a counter clockwise search as shown in Figure 7(C). The remainder of the algorithm remained the same as described in the second part. The robot carried out the three points search and returned to the highest concentration position.

The 0.29 ppm level was taken as the threshold for the fresh air condition. The 0.35 ppm level was taken as the threshold between a low chemical concentration and a high concentration.

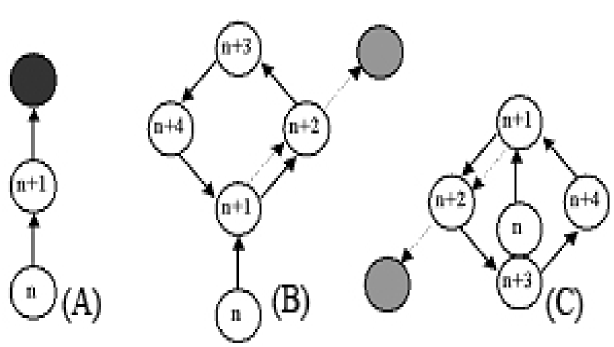

Figure 7. The search control algorithm.

Figure 8 shows a simplified diagram in the style of the subsumption architecture [Brooks, 1991], which illustrates the main control scheme for the system. In this diagram, the sensors are on the left, the behaviours are in the middle and the actuators are on the right. There were three main behaviours in this experiment: search, avoid and congregate. When the cleansing process was finished, the robot leader then released the chemical continuously during the experiment. At the same time, the robots started to search for the robot leader. When the whisker sensors detected an obstacle, it triggered the avoid behaviour. This behaviour took over from the search behaviour. After finishing the avoid behaviour, the search behaviour regained control of the robot. If the robot was in the search mode and it detected a high concentration of methylated spirits that was greater than 4 ppm, this condition would trigger the congregate behaviour. The robot's control would switch to the search behaviour mode again if the concentration fell below the threshold level of 4 ppm. The area defined by a threshold of 4 ppm was chosen as the congregating area for the robots, as can be seen in the Figure 5 (the hatched region).

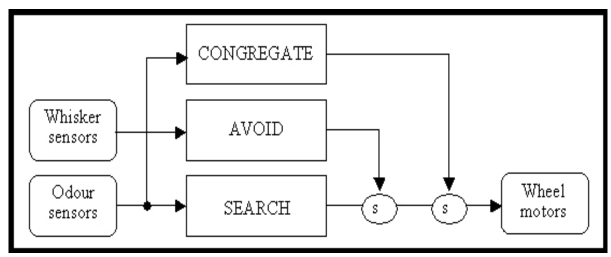

Figure 8. A diagram illustrating the main control scheme for the robots.

In addition, a wireless modem was installed on each robot to allow monitoring of its activities. Figure 9 shows the communications between the PC and each robot. The modem connected to the PC was a master that could dynamically change its address. The control software to access the master modem was written in Java with Java API communication. Each slave modem was configured with a unique address and connected to the micro-controller on the robot. The robot leader was controlled manually using this communication scheme to command it to move and to broadcast the chemical.

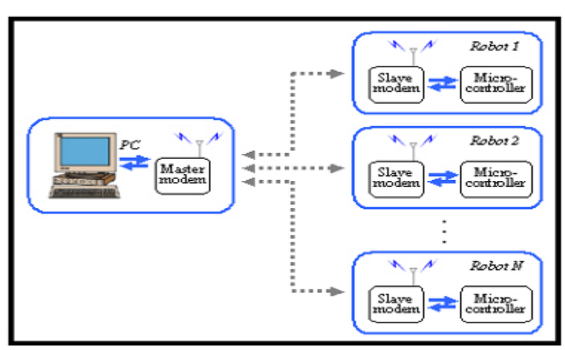

Figure 9. Communications to monitor the status information of each robot.

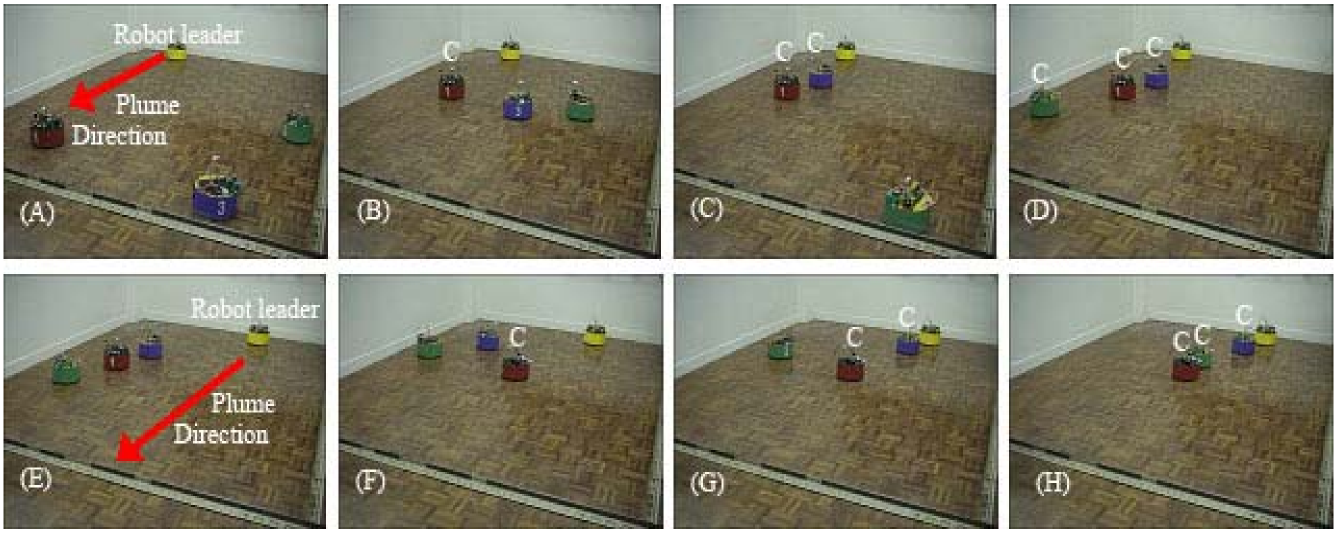

Figure 10. Congregation behaviour using a robot leader and other three robots (C indicates a robot that has congregated in the plume).

4 Experimental Results

Even though the robot only has a single slowly responding gas sensor and without airflow information, the algorithm works well for locating the robot leader and performing the congregating behaviour.

The sequence of pictures in Figure 10 shows the progress of an experiment performing the congregation behaviour. Initially, the robot leader broadcasted a chemical and the others three robots started to search and localize the robot leader (Figure 10(A)). When the robots sensed a high level of chemical concentration (> 4 ppm), the congregate behaviour was executed, as shown in Figures 10(B), (C) and (D) respectively. Half way through the experiment the robot leader was moved to another place (Figure 10(E)). With the drop in chemical concentration, the other robots started to search again and move away from their previous location. As can be seen in Figures 10(F), (G) and (H), they congregated near the new location of the robot leader. The following pictures (Figures 11(A), (B), and (C)) illustrate another experiment exploring the congregation behaviour. Figure 11(A) shows the initial position of the robots and Figures 11(B) and (C) show the congregation behaviour that results from projecting the chemical plume in different directions. In these experiments, the robots were able to complete the congregation task and congregated at the locations directed by the robot leader.

The experiment was run eight times using a robot leader and three robots. A summary of results gathered from the congregation experiments is given Figure 12. The interval plot with a 95% confidence interval for the mean compares the average time required for congregation taken by the first robot (4.5 minutes) followed by the second robot (12.6 minutes) and the third robot (20.3 minutes).

It can be seen from the interval plot that more robots will require more time to complete the congregation task with time increasing approximately linearly with the number of robots. Time to complete the task is extremely variable, and the variability increases with the number of robots. These phenomena can be explained as follows. The increased number of robots tends to increase the possibility of collisions among robots when localizing the robot leader. Another apparent problem is that when there are several robots grouped around the robot leader, they will interfere with other robots and prevent their task from being completed.

5 Conclusions and Further Work

This project has demonstrated that chemical signals can be utilized as a means of communication among a robot swarm. A plume of pheromone chemical provides an invisible guide path between the robot leader and other robots within the group. They can find the robot leader and perform congregation behaviour, even though each

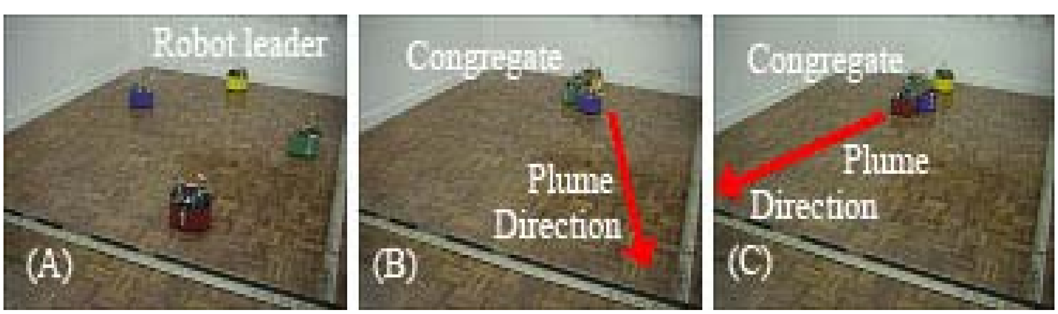

Figure 11. Congregation behaviour resulting from projecting the plume in different directions.

robot only has limited sensors and a simple control algorithm to complete the task.

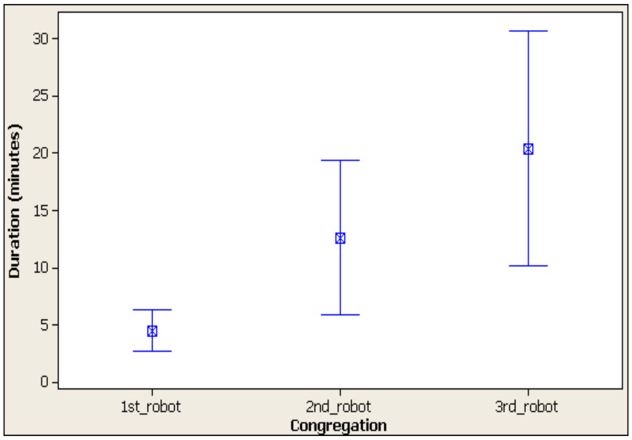

Figure 12. An interval plot of experiment duration statistics.

In this experiment, the robots only used chemical information. In the near future, we will study the combination of chemical and wind information to develop more sophisticated algorithms for the congregation task. We will also develop more complex applications using more than one chemical. In addition, simulation software for the congregation behaviour will be implemented in Java 3D. The simulation will allow rapid testing of algorithms before they are implemented on the robot hardware.

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