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Pheromone communication in a robot swarm: necrophoric bee behaviour and its replication

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SUMMARY

This paper describes a project to implement necrophoric bee behaviour in a robot swarm. Pheromone communication is an effective means of coordinating the activities of insect colonies including food gathering, alarm and defense, reproduction and recognition of conspecifics. In a similar manner it is anticipated that pheromones will provide a valuable form of communication between robots. In order to investigate the problems and potential for this form of interaction, it was decided to implement an example of pheromone communication in a physical robotic system. Inspiration for this project came from the necrophoric behaviour of bees. The necrophoric pheromone released by dead bees triggers corpse removal behaviour in passing worker bees. In the context of a robot swarm one of the proposed applications for this behaviour is to locate and rescue disabled robots that release a pheromone as a form of distress signal. 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 necrophoric behaviour of bees. Results of practical experiments and simulations are also given.

KEYWORDS: Pheromone communication; Robot swarms; Necrophoric behaviour.

I. INTRODUCTION

Biology has always been a source of ideas for those interested in creating robotic systems[1] and it has inspired many of the currently popular approaches to robot system design. This is especially true in the case of simple cooperative robots where the behaviour and characteristics of social insects have been studied and applied.[2–5]

One of the notable characteristics of social insects is their use of pheromones. Pheromones are chemical signals that allow communication between members of the same species.[6–8] Social insects utilise pheromones to cooperate and coordinate their activities, both as individuals and as members of their colony. As a means of communication pheromones have a number of advantages that may be of benefit in robotic systems.

- They demonstrate that a physical path exists between the source and recipient (however, this does not guarantee that the recipient will be able to negotiate the path).
- The range and persistence of a pheromone signal can be tailored by appropriate choice of chemical and its concentration.[9]
- Chemical communication can be used in situations where radio or optical signalling cannot be employed or are undesirable.
- This form of communication does not require a clear line-of-sight path between the sender and receiver.
- Only minute quantities of chemical are required making pheromones efficient and easy to broadcast.[9]

A major concern in pheromone communication is the ability to perform odour localization. A number of robotics researchers have investigated odour localization both for an individual robot[10–15] and groups of robots.[16–19] In most cases these investigations used an alternative signal other than a chemical to transfer information between robots in the swarm. Some researchers have employed a simulation or a virtual pheromone to implement pheromone communication.[20,21] Very few robotics researchers have used actual chemical pheromones in their experiments. One of the few examples of chemical communication that has been reported in the literature involved a chemical trail laid by a robot for other robots to follow.[10]

In order to investigate the problems and benefits that could result from using robot pheromones it was decided to implement an example of pheromone communication in a robot swarm. For this preliminary investigation a simple, well-constrained application was required that was also potentially useful. One of the tasks mediated by a pheromone in social bees is their necrophoric behaviour. This simple activity was selected as an initial candidate for implementation with a robot swarm.

This paper is organized as follows. In Section 2, an overview of the biological inspiration is given, especially the bees' posthumous pheromone. The experimental equipment and robot algorithm are then described in Sections 3 and 4. Next, the robot simulation is considered in Section 5. Lastly, results of real and simulated experiments are provided in Section 6, and conclusions and proposals for future work are outlined in Section 7.

II. BIOLOGICAL INSPIRATION

II.1. Bee pheromones

Bees have been domesticated for millennia and because of their ready accessibility and interesting abilities, they

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have been studied by many scientists from around the world.[2,6,8,9,22–30] One of their notable capabilities is that they can release and sense pheromones using their specially developed olfactory organs. Bee swarms use pheromone communication in food gathering, recognizing hive mates, colony growth, alarm and defence, reproduction as well as necrophoresis.[9,25–27]

The term 'necrophoric' was introduced by Wilson et al. in 1958.[28] It signifies the removal of bee corpses from the hive. When bees die they release the pheromone oleic acid, and this initiates necrophoric behaviour in the other bees. Upon detecting the pheromone, worker bees grasp the corpse and move it a short distance towards the hive entrance. Eventually, this cooperative hygienic behaviour results in the dead bee being ejected from the hive. This process reduces the chances of infection spreading from the accumulation of dead bees throughout the hive.

II.2. Implementation description

One possible application for necrophoric bee behaviour in robotic systems is to rescue disabled robots. This kind of chemically mediated strategy could have applications where a robot suffers a serious problem such as a loss of power or in a situation where communication using radio or light beacons is not possible or desirable.[10] In the case of a total loss of power, a robot could automatically broadcast a chemical signal as a distress call. The chemical would then be carried away by airflow and received by retrieval robots. Finally, the robots would locate the disabled robot by following the pheromone plume and retrieve it cooperatively.

In order to implement this necrophoric behaviour, there are several problems that must be addressed. Firstly, the robots must be able to locate the disabled robot. For this a robust odour localization algorithm will be required. After locating the disabled robot, the rescue robots should be able to move it a short distance towards the retrieval point. In these experiments the retrieval point corresponds to the entrance of the bee's hive and is indicated by a light source. In addition, the malfunctioning robot should be able to broadcast a chemical plume to identify itself and to indicate its position.

III. EXPERIMENTAL SET UP

III.1. Retrieval robots and their sensors

It appears that bees use several sensory systems to implement their necrophoric behaviour.[29] Since necrophoresis takes place inside the dark hive, vision may only be involved in finding the hive entrance with chemical and tactile senses being used to locate and identify the dead bee.

In order to implement the necrophoric behaviour in a robot swarm, suitable sensing components were chosen. Each robot had a tin oxide gas sensor type TGS2600 manufactured by Figaro Engineering Inc. for detecting the pheromone chemical. Three whisker sensors registered collisions between robots and contact with walls surrounding the experimental area. In addition, the retrieval point was indicated by a light source and therefore four Light Dependent Resistors (LDRs) were used to measure the distribution of light falling on the robot and hence indicated the direction towards the light. Practical experiments were performed using two retrieval robots. These robots were 13 cm high, 24 cm diameter and propelled by two side-by-side wheels with a Teflon skid providing a third point of contact with the floor. Each mobile robot was fully autonomous and controlled by an on-board Infineon C167CR microcontroller. Digital outputs controlled power to the tin oxide sensor heater and to the wheel motors. The outputs of the TGS gas sensor and the four light sensors were fed into analogue to digital inputs of the microcontroller. Signals from the three whisker sensors and wheels encoders were read via digital inputs. Figure 1 shows a photograph of one of the mobile robots. Each robot was controlled by a stand-alone program stored in flash memory. The control code was written in C and implemented a set of functions that provided simple access to the robot's sensors and motors. These functions performed the operations of cleansing the chemical sensor, searching to find the disabled robot, locating the light source and pushing the disabled robot towards the light source.

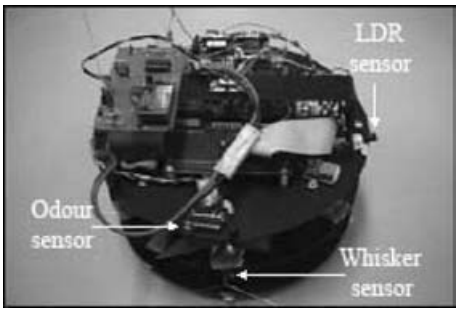


Fig. 1. A retrieval robot equiped with an odour sensor, three whisker sensors and four light sensors.

The cleansing process allowed the tin oxide gas sensor to stabilise. During this process the heater voltage of the sensor was applied for 1 hour before the start of each experiment. Methylated spirits vapor was then broadcast continuously during the experiment by the disabled robot. At the same time, the retrieval robots started to search for the disabled robot using the odour localization algorithm developed in this project.

III.2. Disabled robot or chemical releaser

The retrieval robots were not equipped with any special mechanism for carrying another robot of similar size and weight. Therefore, a light plastic foam artificial robot (also called the disabled robot or chemical releaser) was constructed that contained a battery powered pump and a chemical bubbler to produce a stream of air saturated with chemical vapour. The chemical vapour was fed into a plastic tube with holes that released the chemical around the edge of the disabled robot. The chemical releaser was light enough to be pushed by the retrieval robots and had a height of 12 cm and a diameter of 24 cm. Figure 2. shows a photograph of the chemical releaser robot.

There are two major considerations governing the release of chemical by the malfunctioning robot. First, the chemical releaser must be effective over a long period of time (at

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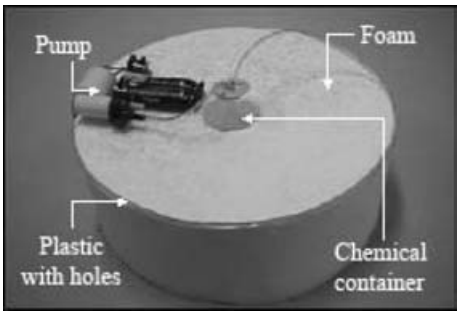


Fig. 2. The chemical releaser artificial robot.

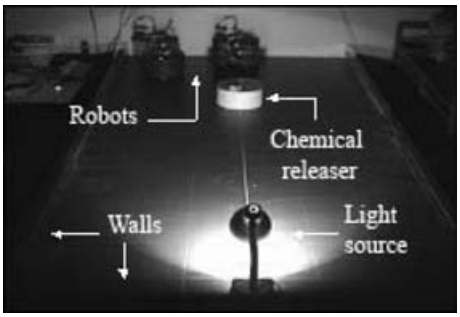


Fig. 3. The table-tennis table experimental arena.

least until retrieval is effected). Second, the rate of chemical release must be adjusted so that the whole experimental region around the robot does not become filled with significant levels of chemical vapour. In order to fulfill these two requirements, the chemical releaser pumped air at a rate of 1 liter per minute through a bubbler containing the robot pheromone. Methylated spirits, a mixture of ethyl alcohol (95%) and methyl alcohol (5%) was used as the pheromone. The odour plume created by the chemical releaser is discussed in the odour distribution section.

III.3. Arena

A table-tennis table 274 cm × 152.5 cm and 76 cm above the floor was used as the experimental arena. Most investigations into robotic odour source location involve environments with significant airflow. It was decided that this investigation would not use artificially imposed airflow because this condition has not been widely considered by robotics researchers and it corresponds to a common situation for many potential robot applications. The experiments were run indoors with only very minor ambient air movement to distribute the pheromone chemical. At the start of each experiment, the chemical releaser was placed about two meters from the light source that represented the retrieval point for disabled robots. The retrieval robots started at a variety of different positions, but one of them was usually located in a corner opposite the light source. To contain the robots, a plastic wall was attached around the edge of the table. A wireless modem on each robot transmitted status information to a PC. The arena layout is shown in Figure 3.

III.4. Odour distribution

As part of the process of designing the robot control algorithm, the typical chemical distribution around the chemical releaser was mapped. The concentration of methylated spirits can be determined by using the following relationship:

$$R \approx R_o K C^{\alpha}, \tag{1}$$

where R is the resistance of the tin oxide sensor, R_o is the sensor resistance in clean air, C is the concentration of the chemical, K is the response coefficient for a particular chemical and type of sensor and α is the sensitivity.[31] This relationship is only applicable over a limited range of concentration. Based on the previous estimates calculated by Russell,[13] the value of $K = 0.67$ and $\alpha = -0.31$.

The distribution of chemical around the chemical releaser was recorded using a TGS2600 tin oxide sensor. Figure 4 show a map of chemical distribution that was built up by recording chemical concentration at a grid of 52 points in a 120 cm × 120 cm area. The chemical releaser was placed at the centre point of the area. At the start of the measurement process the pump was switched on for 3 minutes before chemical readings were recorded. The peak concentration for each of the 52 points was then plotted. It can be seen from these results that a very slow movement of air takes place from the direction of the light source. The observed characteristics of the plume in terms of variability, range, and amplitude were used to help develop the control algorithm.

Figure 5 shows a plot of chemical concentration at 16 points around the chemical releaser measured at intervals during a three-minute period. The points were located at an equal radial distance from the center of the chemical releaser (30 cm). It can be seen that the concentration measured at each point fluctuates considerably. The measured chemical concentrations around the chemical releaser were not distributed evenly even though the chemical releaser was arranged to dispense the chemical equally around its periphery.

IV. THE CONTROL ALGORITHM

IV.1. The odour localization problem

Major constraints that had to be considered when developing a robotic implementation of necrophoric behaviour were the slow response of the tin oxide gas sensor and the random and patchy nature of the chemical distribution created by the chemical releaser. The retrieval robots were not equipped with any direct method of measuring airflow. This is because air movements were too small to be readily measured. Both a turbine airflow meter indicating to 0.1 m/s and a sensitive wind vane did not respond to airflow in the experimental area. Therefore, the odour localization algorithm had to function without explicit airflow information.

In the insect world it seems that odour concentration is averaged over time in order to obtain information from fluctuating and patchy odour plumes.[32] It also appears that information about the spatial distribution of the odour plume is also important.[32,33] Many researchers have studied the structure of odour plumes to try to find features that will assist with the odour localization problem.[11,12,19] Ishida et al[12] mention that even though semiconductor gas sensor are slow the readings that they provide can be used to gather information about the structure of odour plumes.

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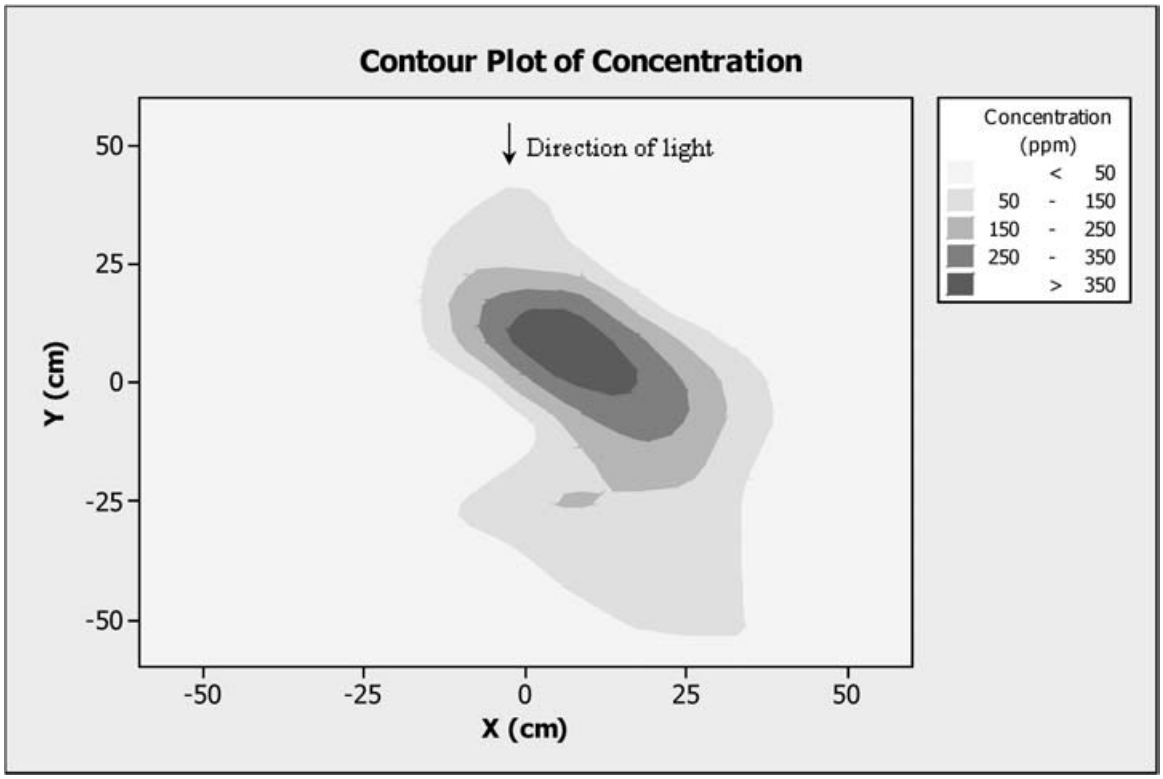


Fig. 4. The chemical distribution surrounding the chemical releaser located at x = 0, y = 0.

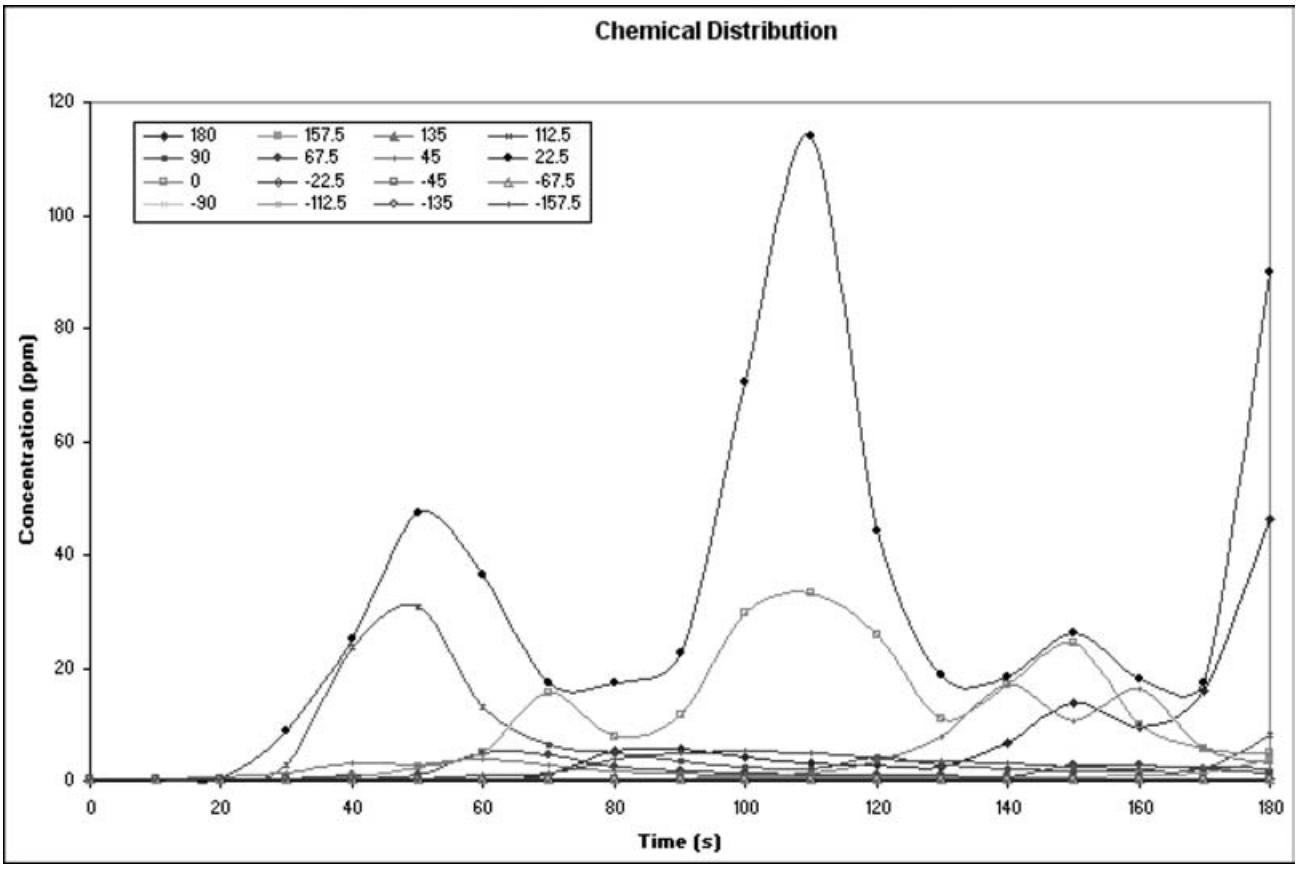


Fig. 5. Time variation of the chemical distribution measured around the chemical releaser.

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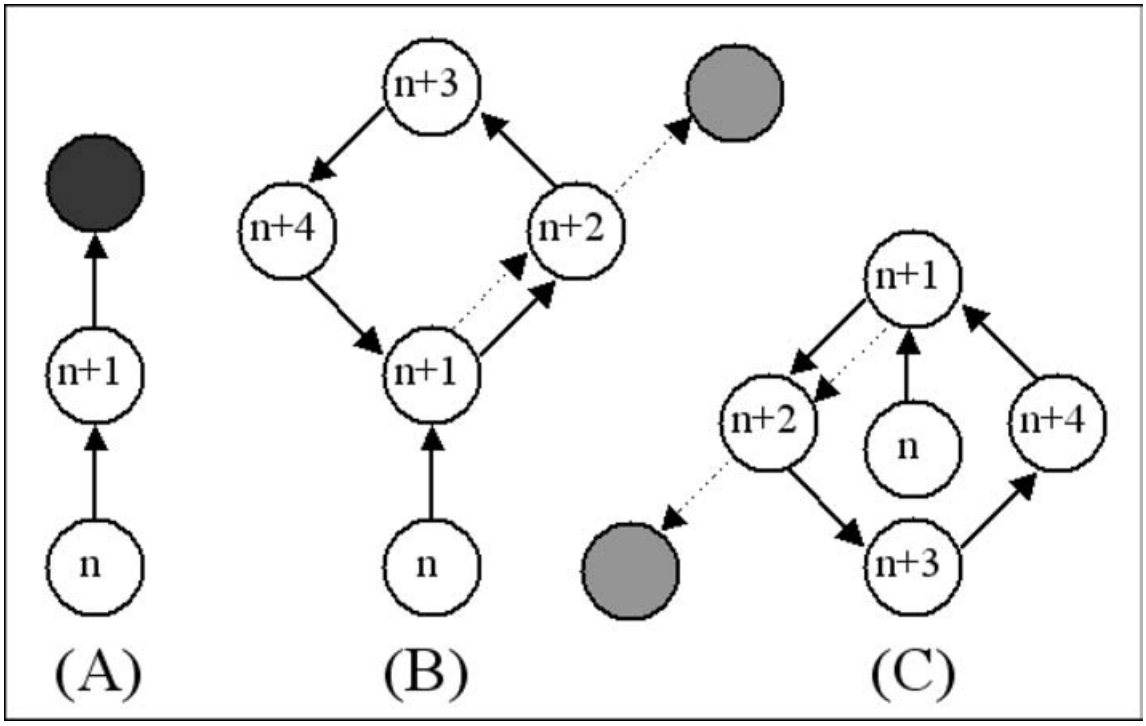


Fig. 6. The retrieval robot control algorithm.

In this project, a series of experiments was performed to help develop and improve a simple control algorithm that could accommodate the characteristics of the tin oxide gas sensor and the chemical plume. Furthermore, although many methods of localizing odour have been described in the literature,[34] it was decided to develop a simple localization algorithm suitable for the environmental conditions of this experiment. The algorithm had to accommodate the robot's dimensions, the characteristics of the gas sensor, the lack of detectable airflow and the shape of the chemical plume that develops in the experimental arena.

In order to allow the gas sensor time to stabilise it was decided that the source location part of the robot control algorithm should consist of a sequence of rapid movements each followed by a relatively long sensing period. If increasing chemical concentration was measured after each successive movement then the robot's program maintained its current heading. This broadly corresponds to the behaviour observed in the *E. Coli* bacterium.[35] There is evidence that the *E. Coli* behaviour for chemical source location is not very effective when faced with significant fluctuation in the chemical readings.[36] For this reason it was decided to select changes of direction based on local gradient information rather than choosing a random heading as is the case with *E. Coli*. In conditions of high chemical concentration it is assumed that chemical concentration readings are relatively reliable and if a fall in concentration is measured then the robot should turn back and take a group of measurements in the direction that it has come from. Random fluctuations are more likely to dominate chemical sensor readings in low concentration regions. To prevent the robot wandering at random when the chemical concentration is low, the robot takes a group of measurements ahead of its current position. This has the effect of encouraging the robot to keep moving ahead and hopefully escaping from the region of low concentration. A detailed description of the odour localization algorithm follows.

IV.2. The robot algorithm

When searching each robot moves forwards in steps of 21 cm with a speed 0.18 s/cm. After each movement the robot senses chemical concentration by taking one reading every second for 20 seconds. Instead of calculating the average concentration value, the highest reading in the 20 seconds interval is recorded. This procedure helps to overcome the rapidly fluctuating nature of the chemical concentration.

The algorithm compares the current chemical reading with the previous reading measured before the step. A 0.3 ppm level was taken as the threshold between a low chemical concentration and a high concentration. The robot search behaviour consists of three main parts.

a. When the chemical concentration is increasing both in low or high concentration conditions, $c_{n+1} \geq c_n$ the robot moves forward as illustrated in Figure 6(a).
b. When the chemical concentration is decreasing in a low concentration condition, $c_{n+1} < c_n$ and $c_{n+1} < 0.3$ ppm, the robot starts to search ahead moving to three points in a counterclockwise sequence as shown in Figure 6(b). The robot records the maximum concentration that it measures at the three positions (c_{n+2}, c_{n+3} and c_{n+4}). It then moves to the highest concentration point ($n+2$ in Figure 6(b)). In this example the chemical concentration at point $n+1$ becomes c_n and the point $n+2$ becomes c_{n+1}. The algorithm is then repeated.
c. When the chemical concentration is decreasing in a high concentration condition, $c_{n+1} < c_n$ and $c_{n+1} > 0.3$ ppm, the robot rotates 180 degrees before performing a counterclockwise search as shown in Figure 6(c). The

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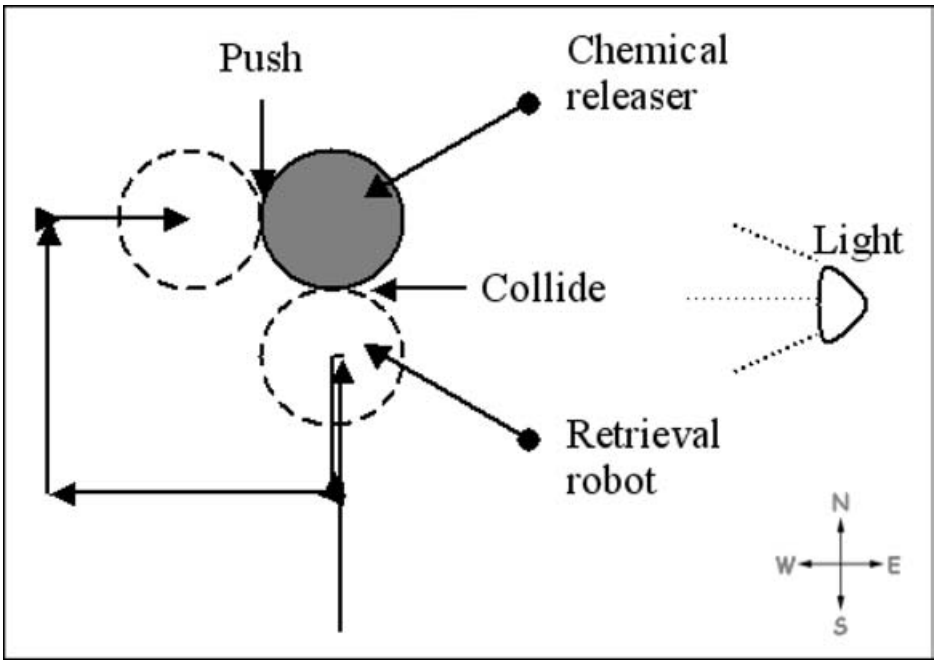


Fig. 7. Pushing the chemical releaser.

remainder of the algorithm remains the same as described in the second part. The robot carries out the three points search and returns to the highest concentration position.

The different search algorithm in low and high concentrations has proved to be effective and accommodates the random and patchy nature of the chemical distribution. This difference allows the robot to localize the chemical releaser without any direct knowledge of airflow direction.

IV.3. The retrieval action

While searching for the chemical releaser, if the robot hits any object its whiskers are activated. The chemical concentration at that point influences the robot's decision whether to push the object or not. The decision can be outlined as follows.

- If the concentration level is greater than 0.5 ppm, the robot tries to push the chemical releaser a short distance toward the light. In order to do this it must first move to position the chemical releaser between itself and the light source. In Figure 7, the robot collides while moving north and the light source is to the east. Therefore, the robot should move around the chemical releaser in the westerly direction before pushing the chemical releaser to the east. The robot's wheels would jam if the robot pushed the wrong object such as another retrieval robot or the sides of the table. After completing a pushing operation the retrieval robot moves away from the chemical releaser before starting to search once again.
- If the concentration level is low, the robot would reverse away from the collision by rotating 180° plus a random angle chosen in the range $\pm 90°$ and then continue its search.

The sequence of searching for and pushing the chemical releaser a short distance is repeated until it is sufficiently close to the light source.

V. ROBOTS SIMULATION

Because of limitations of laboratory space, resources, and time, the experiments with real robots have been limited to a maximum of two retrieval robots. In order to extend our investigations to much larger numbers of robots, it has been necessary to create a simulation. The validity of the simulation was verified by comparing practical and simulated results for one and two retrieval robots. The simulation could then provide useful data for three and more robots.

All of the major features of the real experiment – the retrieval robots, the disabled robot or chemical releaser, the arena and the odour distribution – were simulated as accurately as possible. The simulated robots had a chemical sensor, touch sensors for collision detection and four light sensors for retrieval point orientation. The simulation was prepared for between one and ten robots; however, the number of robots in the simulation could be increased up to 30. Although it would be possible to increase the number of chemical releaser robots, in this simulation experiment, only one disabled robot was included. To accommodate the additional robots the simulated arena was enlarged to 291.67 cm × 416.67 cm for around 10 simulated robots. The simulated odour was modeled using the recorded data mentioned in Section III.4. This recorded chemical data was measured at 52 points within a 120 cm × 120 cm area and gathered over a three-minute interval. These sequences of data points were then cycled through during the simulation process to provide chemical sensor readings. An additional feature of the simulation was that the speed of the simulation could be varied. In the real experiments, the speed of the robots was 0.18 s/cm when moving forward or backward and 0.028 s/degree when rotating.

The overall structure of the simulation was designed so that it closely replicates the actual physical experiments. Therefore, it also implemented the odour localization algorithm and the retrieval action of the real robots. The

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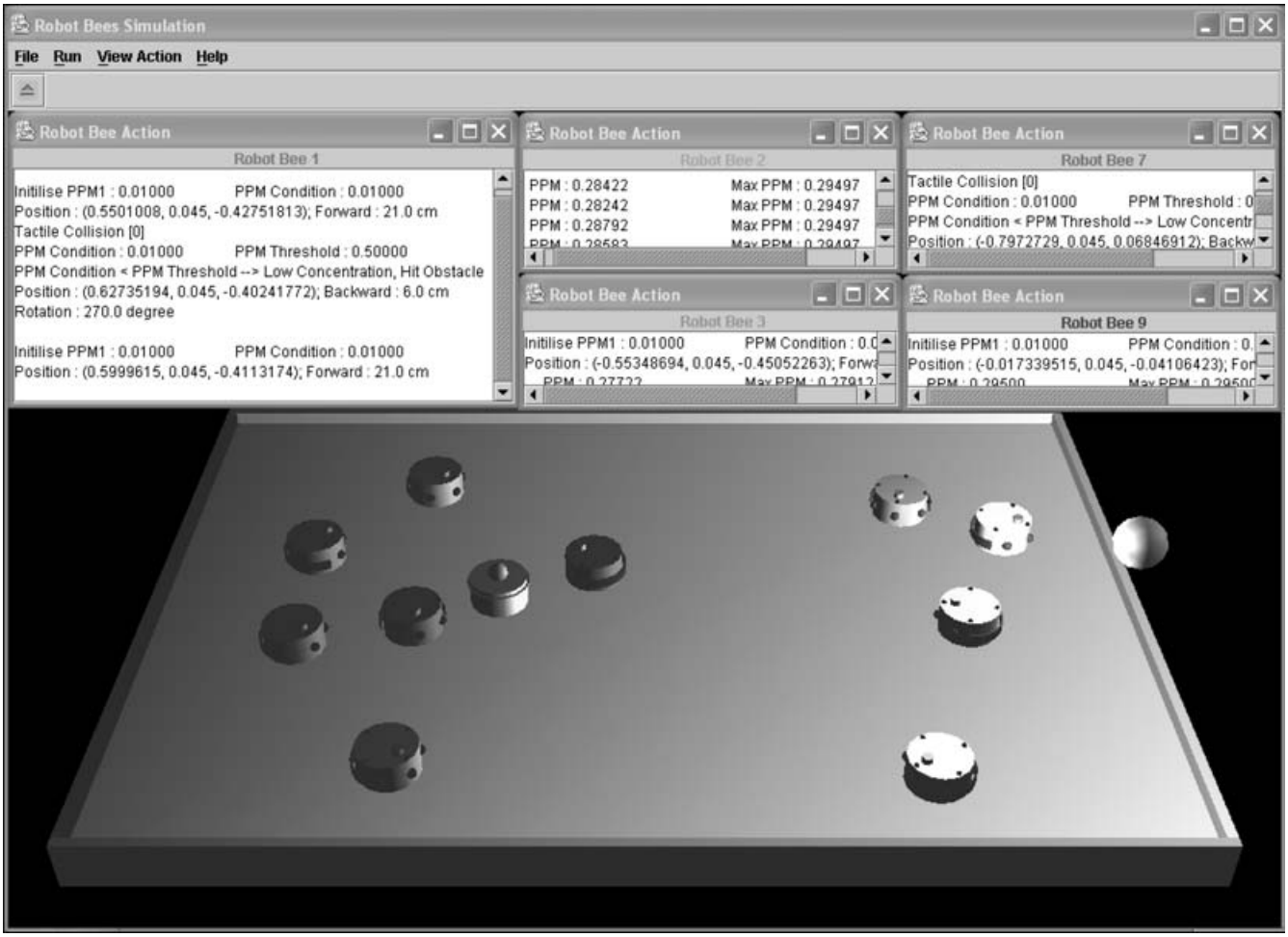


Fig. 8. A screen shot of the robot simulation.

only exception was elimination of the cleansing process for the tin oxide gas sensors.

The pheromone robotics simulation was programmed in Java 3D version 1.3.1. The Java 3D package is an effective way of creating three-dimensional graphics because it provides a high-level object-oriented view of 3D graphics.[37,38] Java 3D enables us to work with high level constructs for creating and manipulating geometric objects and it implements the functionality and graphics acceleration provided by OpenGL or DirectX. A scene graph is used to create a tree like structure containing nodes that represent objects to be rendered. This graph consists of objects that describe geometry, sound, lights, location, orientation, and appearance. We can therefore create the three dimensional structure of a robot including all necessary components such as sensors by placing them in the scene graph.

The simulation requires a reasonably powerful computer in terms of the graphic card, memory usage, and processing power of the CPU. Currently an Intel Pentium 4 CPU 3.00 GHz, with 1GB RAM and 128 MB double data rate frame buffer video card is being used.

Figure 8 shows a screen shot of the robot simulation. Initially the chemical releaser is placed on the centerline of the experimental area at a distance equivalent to two-third of the experimental area width from the light source. At the start the retrieval robots are placed randomly in the experimental area. Every action of individual robots can be easily monitored by sending data to separate window frames. Both the retrieval robot paths and disabled robot path are captured and can be plotted after the experiment is finished.

In this simulation, a summary of important activities is also recorded, such as, the duration of the experiment, the number of times the disabled robot is pushed by the other robots and its positions, and the number of times a robot attempts to push the wrong object (either another retrieval robot or the walls). This information is then available for further analysis.

VI. EXPERIMENTAL RESULTS

Although the retrieval robots only have a single slowly responding gas sensor the algorithm works well for localizing the chemical releaser. The robots can find the chemical releaser and push it even when they start well away from the chemical plume.

VI.1. Physical experiments

The sequence of pictures in Figure 9 show a single robot performing the necrophoric behaviour. The chemical releaser was placed in the middle of the table between the retrieval robot and the light source Figure 9(a). In this experiment, the robot was able to complete the task of pushing the chemical releaser to the light source. During the experiment

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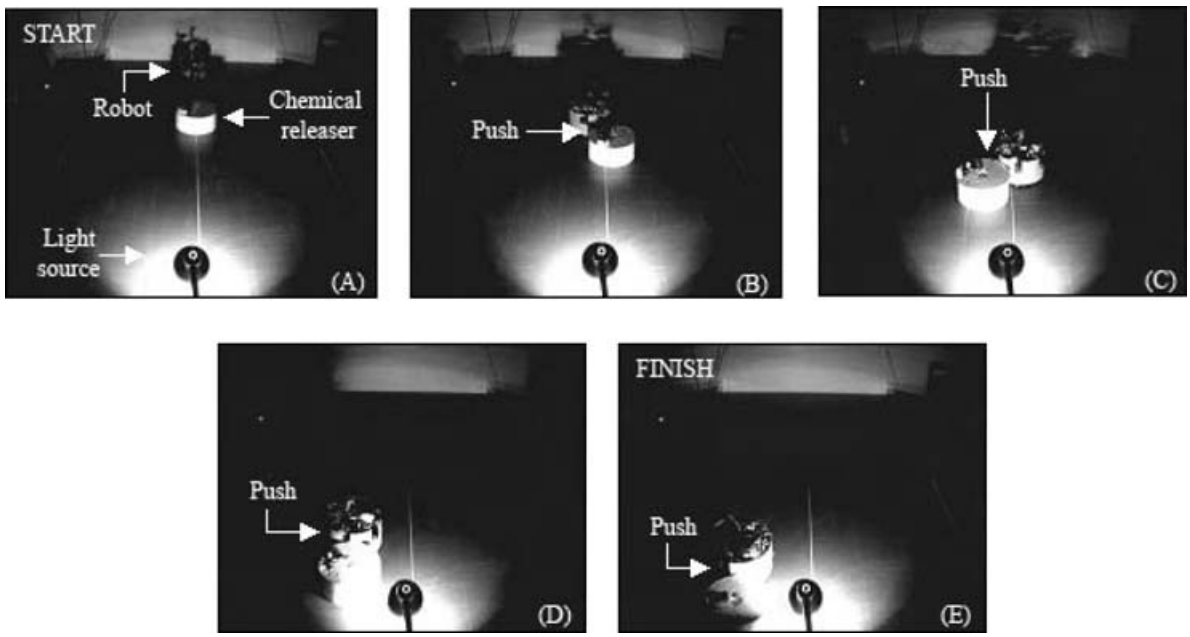


Fig. 9. The chemical releaser is moved towards the light by a sequence of discrete pushes from a single robot.

the robot detected the chemical releaser, then turned to face the chemical releaser and pushed it a short distance towards the light source. The robot then moved away from the disabled robot before starting its search again. The following pictures (Figure 9(b), (c), (d) and (e)) were taken at those points when the robot started to push the chemical releaser.

Figure 10 illustrates another experiment using two retrieval robots. This corresponds to nature where it is usual for more than one bee to be involved in moving the corpse towards the hive entrance. The two robots were also able to complete the task. Pictures Figure 10(b), (d) and (f) were taken when one of the robots started to push the chemical releaser robot towards the light source. In the experiments, if a retrieval robot hit the another retrieval robot or table sides in a high concentration of chemical, the robot tried to push the other robot or the table sides as shown in Figure 10(c) and (e) respectively. In Figure 10(c), the robots collided and both of them then tried to push each other. After a while, they stopped pushing if their wheels jammed or if they considered that they have completed their push. They then moved backward and performed a random turn. It was also possible that two robots pushed the chemical releaser at the same time. In this case, there would be no problem as long as they did not interfere with each other. In each of the error conditions the situation was resolved when the robot finished its push and moved away.

Summaries of results gathered from physical experiments are given in Table I and Figure 11. The box plot assesses

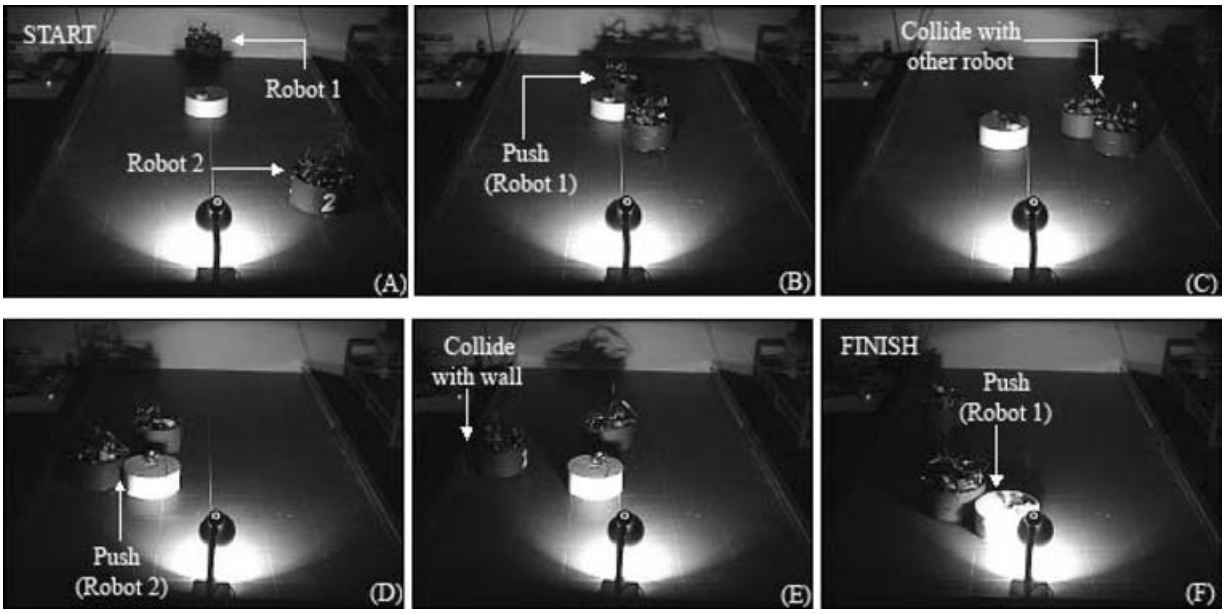


Fig. 10. The necrophoric behaviour exhibited by two robots.

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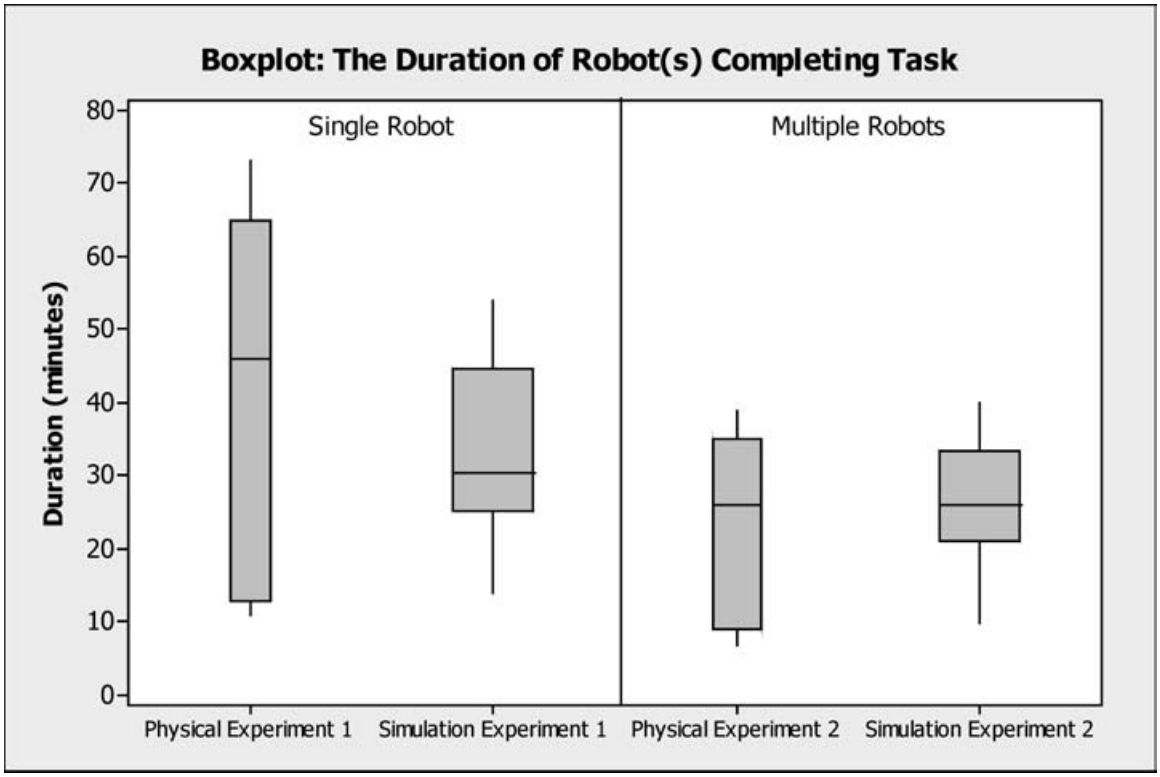


Fig. 11. A boxplot of experiment duration for both physical and simulation experiments.

Table I. A summary of experiment duration statistics for both physical and simulation experiments (used single and multiple robots).

		Statistic Data		
Experiment	Robot(s)	Number of trials	Mean (minutes)	Standard deviation (minutes)
Physical Experiment	Single	5	40.40	26.80
	Multiple	7	23.71	12.07
Simulation Experiment	Single	20	34.05	11.90
	Multiple	20	26.20	8.05

and compares the sample distributions of task completion times for one and two robots. Results of the variance F-test and Levene's test for these experiments indicated that the p-values were greater than a reasonable choice of α (0.05). Therefore, it was appropriate to assume equal variance when using a two-sample t-procedure to compare the means for the experiments. With a 95% confidence interval the difference between the two population means was 16.7 ± 25.5 minutes. It was observed that the physical experiment duration for a single robot was between 8.6 minutes faster and 42 minutes slower than the experiment duration for two robots. Therefore, a single robot was usually but not always slower than two robots.

VI.2. Simulation experiments

As far as possible all properties of the real robot experiments have been replicated in the simulation software. Table I and Figure 11 present a summary of the simulation experiment statistics. For these experiments the simulated arena size matched the physical arena. These data were used to check the validity of the simulation by computing a confidence interval and performing a hypothesis test of the difference between the population means of the experiment duration for physical and simulation experiments.

Results of the variance F-test and Levene's test for these experiments indicated that the p-values for a single robot were less than the reasonable choice of α (0.05) and the p-values for two robots were greater than α (0.05). Therefore, unequal variances were assumed for the two-tailed two-sample t test with significance value α equal to 0.05 for both the single robot and two robot experiments. The null hypothesis was that the two means were equal for both cases.

Firstly, the physical and simulation experiments for a single robot were compared. The results showed that the 95% confidence interval was $(-27.77, 40.47)$ which includes zero, thus suggesting that there is no significant difference in the means. Next, hypothesis testing resulted in a p-value of 0.633. Since the p-value was greater than the chosen α-level, there was no evidence for a difference in the mean duration for a single robot to complete the task between physical and simulation experiments. A comparison of the physical and simulation results for two robots gave a 95% confidence interval of $(-14.08, 9.11)$ and the p-value (0.628) for the hypothesis test. These tests indicate no significant difference in duration for completing the task using two robots. These tests support the validity of the simulation when compared with experiments with one and two physical robots; the simulation experiments were then used to study the necrophoric behaviour in larger groups of robots.

Figure 12 shows a series of results taken from a simulation experiment. In this case, three retrieval robots had the task

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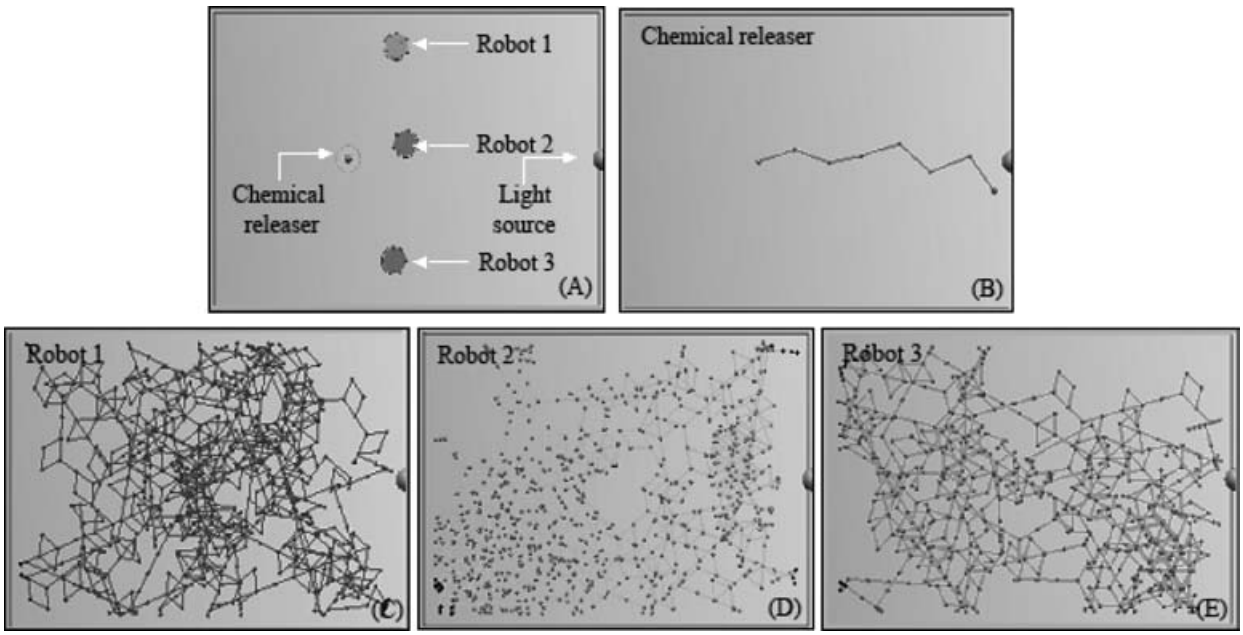


Fig. 12. The paths taken by the robots in a simulation experiment involving three retrieval robots.

of recovering one disabled robot. The initial state of the arena is shown in Figure 12(a). During the experiment the path taken by the chemical releaser is shown in Figure 12(b). In this experiment, the chemical releaser was pushed 7 times by the coordinated action of the three robots. The remaining figures (Figure 12(c), (d), (e)) give the paths taken by robots 1, 2 and 3, respectively, while performing the retrieval behaviour. It can be seen that the path of each robot covers almost the entire arena while searching for the chemical releaser.

One failure mode for the necrophoric algorithm occurs when a retrieval robot collides with another retrieval robot or the walls in a high concentration of chemical. In these situations the robot 'believes' that it has located the chemical releaser and tries to push the wrong item. This failure mode was modeled in the simulation. For the simulation experiment shown in Figure 12 the number of times a retrieval robot attempted to push another retrieval robot was 14 and the number of times the tablesides were pushed was twice. When a robot/bee discovers a disabled robot/dead bee, it seems reasonable to ask why it should not complete the task instead of only moving its burden a short distance. From both the physical and simulation experiments it seems that this behaviour has an important function in overcoming errors in identifying the correct target. It also helps where the disabled robot becomes obstructed or jammed and needs pushing from a slightly different direction.

Simulation experiments were run for 14 different group sizes of retrieval robots with 10 trials for each individual group size. From the simulation experiments, it is clear that the disabled robot can be localized and retrieved even when there is a large variation in the number of retrieval robots involved.

It can be seen from the box plot Figure 13(a) that the time required for the chemical releaser to be retrieved is extremely variable, especially for a small number of retrieval robots. The time to complete the task is affected by such variables as the starting position of the retrieval robots and the chemical releaser within the arena and the density of robots. Although the removal task took longer in a less crowded arena, the task completion time was not improved significantly with more than 6 retrieval robots. One reason for this can be gathered from Figure 13(b). Not every retrieval robot pushes the disabled robot and the number that do seems to be limited to about 5 when the total number of robots exceeds 9.

As the number of robots increases then the possibility that an attempt to push the chemical releaser will be blocked by the presence of another robot also increases (Figure 14). In addition the number of incorrect pushes increased in proportion to the total number of robots in the arena (Figure 13(c)). An incorrect push happens when a robot tries to push another retrieval robot or the arena walls resulting from detecting a collision in a region of high chemical concentration.

It may seem that the necrophoric task could be completed quicker if a robot continued to push the chemical releaser all the way to the light source without stopping. However, with a simple control strategy there are a number of situations where this would not work. If the odor from the chemical releaser keeps on recruiting robots to the task, eventually there will be so many robots grouped around the chemical releaser that they will interfere with each other and prevent the task being completed.

Also, if a robot mistakenly identifies a wall or another functioning robot as the chemical releaser this situation will be corrected after the robot tries to push the mistaken object for a short while. In the real world, if too many workers bee were committed to this task, this would also result in inefficiency.[30] In bee colonies, only 1% or 2% of the workers have the task of removing corpses.[29]

It can be seen from these experiments, that there are several advantages for cooperative robot behaviours. If one robot fails, the other robots can still finish the task. Another advantage is that if the working area is relatively large,

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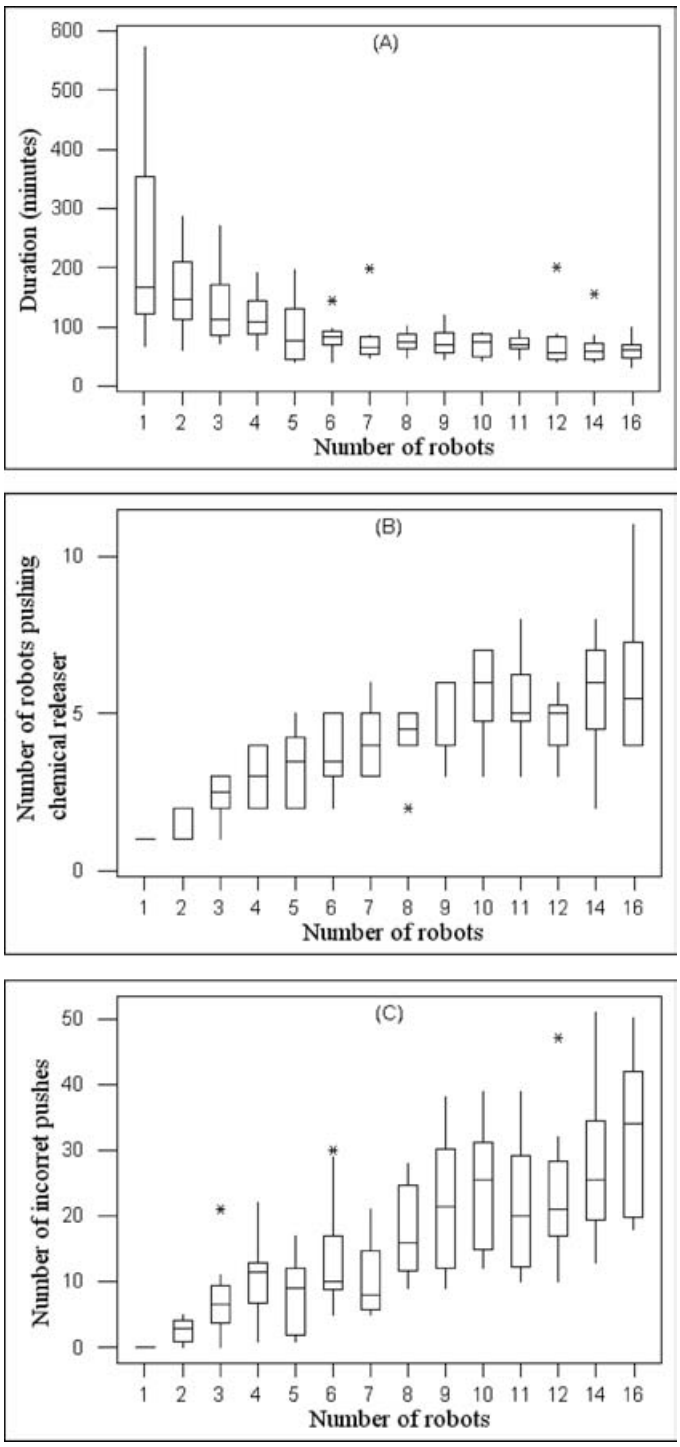


Fig 13. The box plots indicating some of the effects of swarm size on the performance of the retrieval task.

an increased number of robots complete the task quicker compared to a single robot.

VII. CONCLUSIONS AND FURTHER WORK

Pheromone communication for robots has a number of advantages that are not available from alternatives such as radio communication. Plumes of pheromone chemical provide a guide path between the source and receiving robot. Chemical signals could also be released by a fail-safe mechanism that is activated when a robot becomes disabled.

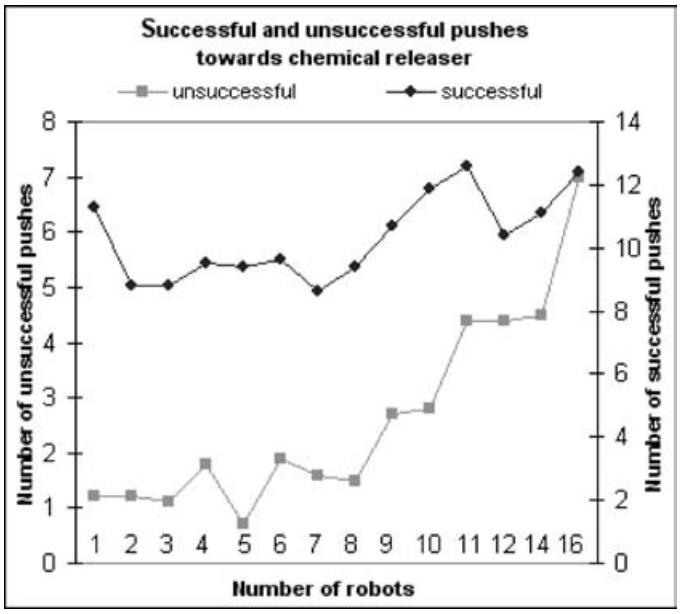


Fig. 14. The number of succesful and unsuccessful attempts to push the chemical releaser.

This could act as a call for assistance as in the current experiments. In this project two mobile robots have been built and programmed to perform a rescue task based on the necrophoric behaviour of bees. A simulation of the necrophoric behaviour has also been successfully developed in Java 3D to help in understanding the essential aspects of pheromone communication as well as significantly decreasing the time to perform experiments. The odour localization algorithm developed for this project works well both in the physical and simulation experiments. With the aid of chemical communication effective rescue behaviour was produced using elementary sensors (contact, chemical strength and light intensity) together with a simple control algorithm. Both simulated and physical experiments have shown that the necrophoric rescue algorithm produces effective results with a wide range of swarm sizes and can recover from a number of different failure modes. The limited resources required by this kind of chemical mediated behaviour would make it applicable to even the simplest of robots. In this initial experiment the robot(s) only interact with the disabled robot or chemical releaser. In the future, we will study more complex interactions between robots using more than one chemical. As the design of the simulation software was made very general its adaptation to future experiments can be easily implemented.

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