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Bi-directional pheromone communication between robots

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SUMMARY

This paper describes a project that aims to demonstrate two-way communication between robots using chemical signals. The project is part of a wider investigation examining the potential advantages and drawbacks of implementing pheromone signalling between robots. It is well known that all kinds of biological creatures use chemicals as a means of attracting, repelling, controlling, guiding and informing their fellow creatures. This very wide range of effective biological forms of chemical communication is the inspiration to look at potential robotic applications. In previous work involving the use of physical chemical signals in robotics the case of one robot releasing or depositing a chemical for other robots (or the same robot) to detect and act upon has been addressed. This project moves a step forward to investigate a group of robots where each group member emits and detects pheromone chemicals. The example task addressed in the project is to use chemical signalling to help a collection of robots to assess group size. Bacteria provide a model for this kind of chemical communication. By monitoring chemical concentration bacteria can assess group size and hence modify their behaviour as appropriate. Although not intending to model bacterial quorum sensing in detail this behaviour provides inspiration for our demonstration of bi-directional communication. This paper provides details of the implementation of quorum sensing in a group of robots. The robots used in the project, their control algorithms and experimental results are presented. Both beneficial aspects and the pitfalls of pheromone communication in robotic systems are also discussed.

KEYWORDS: Pheromone communication; Group size; Robotics.

1. Introduction

Scientists involved in developing robotic systems often look to nature for insight and derive inspiration from biological organisms. This work has also drawn inspiration from biology and in particular pheromone communication in living organisms. Pheromones serve a number of functions for living organisms, including identification, recognition, aggregation, facilitation, attraction, alarm propagation and group decision making.[1–5] A pheromone is defined as a substance emitted by an organism into the environment that causes a specific reaction in a receiving organism of the same species.[6,7] Therefore, to perform pheromone communication, a robotic system must display the following characteristics: the pheromone chemical is released by a robot; the pheromone chemical is detected by another robot or other robots in the group; and the pheromone chemical elicits a specific response in the receiving robot or robots.

Currently, pheromone communication has not been widely studied in the robotics context. This is partly due to the relatively early stage of development in robotic chemical sensing, which is the major component in pheromone communication. Research involving robot chemical sensing mainly focuses on odour identification,[8,9] odour localisation[10–20] and odour distribution.[15,18,21] In most cases where robot pheromone communication has been investigated, an alternative signal other than a chemical has been used to transfer information between robots. Russell,[22] inspired by pheromone trails used by social insects, developed short-lived navigational markers for small mobile robotic systems where heat trails were used to replace pheromone trails. Sugawara *et al.*[23–25] also investigated the use of pheromone trails in different applications: foraging behaviour, collective behaviour and traffic flow in multi-robot systems. In these cases, pheromone trails were replaced by graphics projected on the floor. In their work, Svennebring and Koenig[26] studied terrain-covering robots equipped with a black pen to mark trails on the floor. Other researchers, Payton *et al.*,[27–29] explored virtual pheromone that was sent and received via an infrared transmitter and receiver. None of these studies used physical chemicals as a means of communication among robots. There have also been a large number of works involving pheromone simulation but these do not address the practical considerations which are an important component of the current project. At Monash University, we have implemented pheromone communication between mobile robots for several applications. These include depositing pheromone trails by one robot for other robots to follow,[30] rescue by a robot swarm of disabled robots that release a pheromone,[31] congregation behaviour in a robot swarm using a pheromone[32] and guiding robots' behaviour using pheromones.[33] These previous experiments were limited to the use of one-way communication from a single source robot to a number of receiving robots. In this project, we investigate the possible situations where each robot can both transmit and receive pheromone information. In order to focus on a particular application the problem of controlling group size in multi-robot systems using pheromone communication has been addressed.

The term '*quorum sensing*' describes the regulation of bacterial gene expression by means of population sensing.[34]

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Bacteria emit a pheromone signal and this allows an individual bacterium to monitor the presence of other bacteria and hence sense population density.[5,35] The concentration of the pheromone sensed is proportional to the current number and proximity of bacteria and this provides bacteria with a mechanism for assessing adjacent population density.[36] When a minimum unit or 'quorum' of bacteria has been reached; it allows bacteria to coordinate their activities as a group.[4,5,34–37]

It was decided to implement a similar form of quorum sensing for a group of robots as a vehicle for investigating robotic bi-directional chemical communication. In a previous investigation,[32,33] pheromone attracted and directed recipient robots to a specified congregation area in a manner similar to the way social insects use pheromone templates for building structures. In the project reported here, each robot that arrived in a specified location released pulses of chemicals while at the same time monitoring pulses of chemical from other robots. Information about the frequency of pulses allowed the robots to estimate group size and then change their group action when a quorum was reached. In this case, once a quorum had been achieved, the robots executed a light-seeking behaviour. The problem of controlling group size in multi-robot systems has been explored by several researchers, including Holland and Melhuish.[38,39] In this project, we would like to use this problem to highlight the application of bi-directional pheromone communication in robotics.

There are a number of potential advantages for the use of pheromone communications in robotics. The range and persistence of a pheromone can be tailored by appropriate choice of chemical and its concentration whereas other signals such as wireless, optical and acoustic can only be detected close to the time they are produced.[2,40] Pheromone messages may persist long after the signaller has gone, such as pheromone deposited by an antelope for territory marking remains after the animal has moved on.[40] Very volatile chemicals have a short persistence that extends to medium persistence for low-volatility chemicals and indefinite persistence for non-volatile chemicals. The transmission of chemical signals is not limited by line-of-sight. For this reason, pheromone communication might overcome problems involving other robots obstructing or blocking light signals.[41–43] Chemical signals could also propagate through cluttered environments that might block other forms of signalling. The signalling function of pheromones can provide additional information gathered on the way between source and recipient, such as its attenuation through time and distance. Further, this information can include pheromone diffusion gradient which provides an indication of obstacles encountered by the pheromone plume.[27] Detection of a pheromone signal indicates the presence of and traces out an unobstructed path between the source and the recipient. However, it does not guarantee that the robot will be able to negotiate the path. Currently, relatively large quantities of chemical are required (of the order of cubic centimetres per minute) to match sensors with sensitivities of the order of 1 ppm. However, biological sensors show that sensitivities of 1,000,000 times better should be attainable with a corresponding decrease in the quantity of pheromone chemical. With improvements in sensing technology it is entirely possible that a robot could carry a lifetime supply of chemical. Thus a pheromone signal is simple and potentially inexpensive in terms of the cost of production[44] but provides valuable information. Biology shows that pheromone communication works for creatures ranging in size between a bacterium and an elephant – a range of linear size of 1:1,000,000. In addition, chemical signalling is possible in both fluid and air environments. With improvements in technology, it seems reasonable to assume that applications for robotic pheromone communication will develop for robots at some size scale operating in a particular environment. Having alternative forms of communication may provide an advantage of providing stealthy communications, less subject to jamming and interference. However, with the current state of chemical sensing technology and at the size scale and in the environment of current experiments robotic pheromone communication provides many challenges, such as the limitation of the robot speed caused by the slow response of the chemical sensor and the limitation of the number of distinct messages that could be transferred among robots caused by the lack of selectivity of the chemical sensor.

2. Pheromone Communication

To perform pheromone communication a sequence of three processes is required. Firstly, a pheromone signal must be formed and it must consist of the appropriate chemical/s released in the correct time sequence. The second process involves transfer of the pheromone signal from the releaser to the receiver. Thirdly, a detection process for the pheromone signal is required at the receiver. These processes are described below followed by an explanation of how these mechanisms function in this project.

2.1. Pheromone signal production

The choice of pheromone chemicals and method of deployment are considered under this section. One of the factors determining the selection of pheromone chemicals is the transfer medium to carry the pheromone between robots and the type of transmission.[45] Air or water can be a medium to transmit pheromone signals and fluid currents; diffusion and contact are possible methods of transfer. In order to disperse effectively, airborne pheromone must be volatile and waterborne pheromone must be water-soluble. An increase in pheromone molecule size corresponds to a reduction in volatility. Airborne pheromone molecules larger than 20 carbon atoms cannot be effectively diffused.[45] Other factors that influence pheromone selection would include the availability of suitable sensors together with chemical cost and toxicity. Once a pheromone chemical has been selected then methods must be devised for storage on the robot and for releasing it under computer control.

2.2. Pheromone transmission

As stated above, there are three possible ways to transmit a pheromone signal. Volatile or soluble pheromone signals

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can utilise currents flowing in air or water to carry the signal to the receiver. In the absence of any current, the releaser can utilise diffusion. However, except on a very small scale or in a viscous fluid there will always be currents that distribute chemicals quicker than that by diffusion. On the other hand, in the case of a pheromone deposited on the substrate, the receiver can move towards the pheromone signal and detect it by direct contact or by detecting the volatile components that it gives off. The viable transmission distance depends on the strength of the pheromone signal. Both in the air or water medium, the longer a pheromone signal is released, the stronger it is and the wider is the area where it can be detected.[45] The area within which a receiver can still detect the pheromone signal from the releaser will be called the active region. However, when information needs to be exchanged rapidly a long duration for a pheromone signal is not suitable. Furthermore, while transmitting a pheromone signal, the effects of interfering signals from other releasers and other noise sources have to be considered.[46] The form, timing and intensity of pheromone signals can also be affected by environmental factors, such as varying temperature which results in changing volatility and hence changing concentration of airborne pheromone.[46]

2.3. Pheromone detection

The response of a chemical sensor to a pheromone signal must be significantly distinct from its background response to allow the receiver to identify the signal.[46] There are a number of requirements that limit the kind of pheromone sensors that can be used in robotic applications. These requirements include good sensitivity, speed of operation of the order of seconds, low power consumption, small size, robustness and reasonable cost.[12] There are several chemical sensors, which meet these requirements and that have been tried in robotic applications. These include metal-oxide semiconductor sensors, conducting polymer sensors and quartz crystal microbalance sensors.

At Monash University a series of experiments has been conducted to study aspects of pheromone communication in robotics. In a previous experiment,[32,33] a group of responding robots was programmed to gather in a congregation area defined by the pheromone plume created by a robot leader (Fig. 1). Work reported in this paper can be considered to be an extension to that experiment. Responding robots gathering in the congregation area monitor and respond to the group size. This scenario provides a framework for investigating bi-directional communications using pheromones. Note that in order to avoid interference caused by the other pheromone signals and airflow produced by the robot leader these were switched off during the group size investigation.

By analogy with the quorum-sensing process of bacteria, each individual robot in a specified congregation area releases pheromone pulses. Thus an individual robot can monitor the presence of other robots and estimate the group size by detecting the pulses. Instead of using the summation of pheromone concentration as employed by bacteria, group size is determined by counting the number of pheromone pulses released by neighbourhood robots over a fixed period of time.

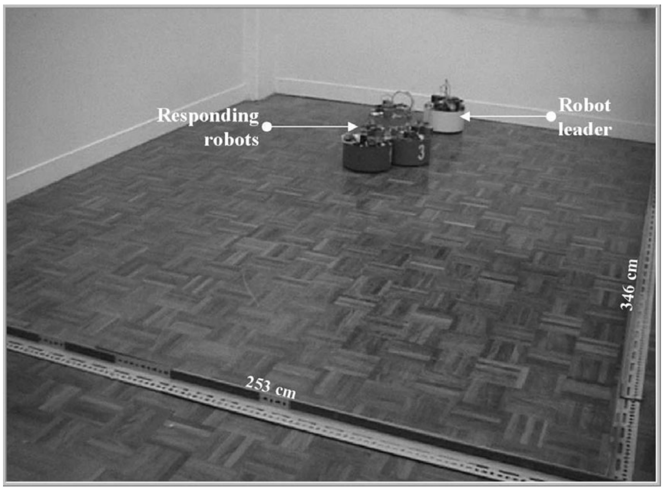

Fig. 1. Congregation behaviour using a robot leader and three responding robots (the experimental area measures 253 cm × 346 cm).

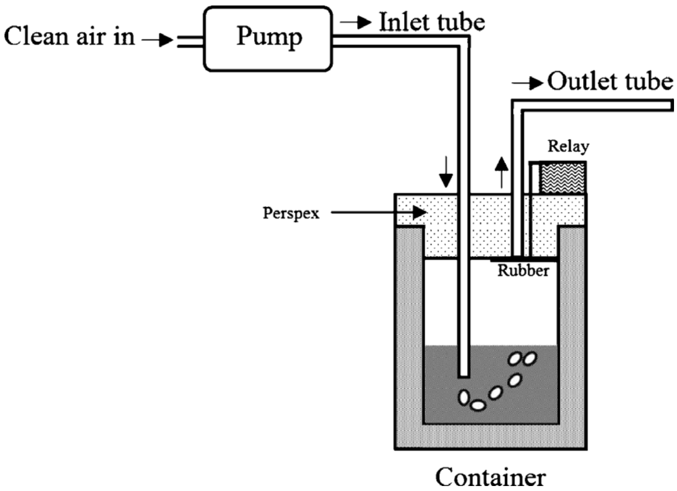

Fig. 2. The pheromone release system.

2.4. Experimental preparation: pheromone production

Each robot requires the capability of carrying and releasing a pheromone chemical. Therefore, an appropriate chemical handling and broadcasting system is required for each responding robot. This system must be light and compact so that it will not affect the mobility of the robots. A chemical bubbler system[47] consisting of a small electric pump and a chemical container were developed to produce a stream of air saturated with chemical vapour by bubbling air through liquid chemical. Figure 2 shows a diagram of the pheromone releasing system. On the outlet side, a separate solenoid valve was added to control the chemical release. This solenoid valve was incorporated to anticipate the use of more than one pheromone chemical. To disperse the chemical more evenly, the chemical vapour was fed into a perforated plastic tube that released the chemical around the edge of the responding robot (Fig. 3). The pheromone chemical chosen for this application was methylated spirits. This volatile colourless liquid consists of a mixture of 95% ethyl alcohol and 5% methyl alcohol.

All of the mobile robots used in this project were based on the chassis of the laboratory robot LABOT

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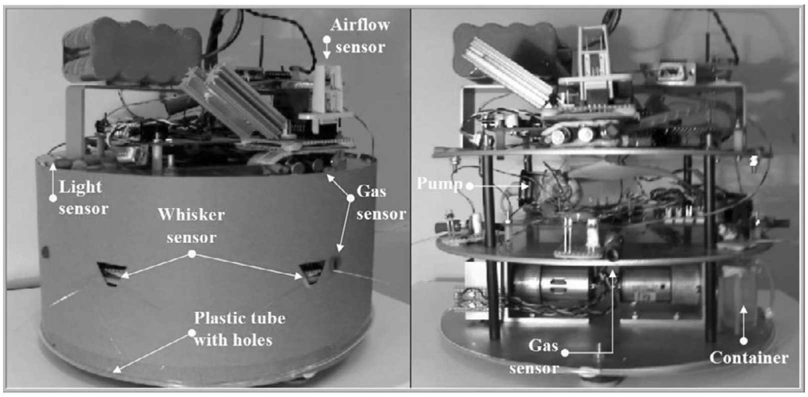

Fig. 3. Photographs of a responding robot.

developed at Monash University. The dimensions of the robots are approximately 13-cm high and 24-cm diameter. A stand-alone program stored in the flash memory of an on-board Infineon C167CR microcontroller controlled each robot. The chemical bubbler system for generating the pheromone signal was attached to the robot chassis. Sensory inputs were provided by four light-dependent resistors for measuring the distribution of light falling on the robot, three whisker sensors registered collisions between robots and contact with walls surrounding the experimental arena and four TGS2600 tin oxide gas sensors detected the pheromone chemical. Each of the robots was also equipped with a wireless modem to allow monitoring and logging of their activities by a remote PC. Figure 3 shows photographs of one of the responding mobile robots used in the experiments. Three identical responding robots were constructed to perform practical experiments. Experiments were performed in an arena measuring 346 cm × 253 cm that was enclosed by a low barrier to contain the robots.

2.5. *Experimental preparation: pheromone transmission*

Each pulse of chemical released by a robot results in a chemical plume surrounding the releaser. Preliminary experiments were conducted in order to investigate the nature of this chemical plume. Measurements showed that chemical concentration around the releaser was not distributed evenly even though the releaser was arranged to dispense the chemical equally around its periphery and the experiments were performed in conditions where there was no measurable airflow. Figure 4 shows a plot of chemical concentration at 16 points around the releaser measured at intervals during a 2-min period with air pumped through the bubbler at a rate of 1 l/min. The points were located at an equal radial distance from the centre of the chemical releaser (30 cm). It can be seen that the concentration measured at each point fluctuates considerably.

The chemical plume surrounding the releaser must contain a sufficient concentration of the pheromone chemical that can be detected by other robots within the region where the group of robots is gathering. The chemical plume is also required to be effective over a certain period of time and at least until other robots sense it. Further, the rate of release of chemical pulses must be adjusted so that the active space around the robot does not become filled with significant levels of chemical vapour. In order to fulfil these requirements, the following experimentally determined parameters were selected: a rate of release of pheromone chemical of 1.5 l/min and a 10-s chemical pulse duration. These choices are discussed further in Section 3.

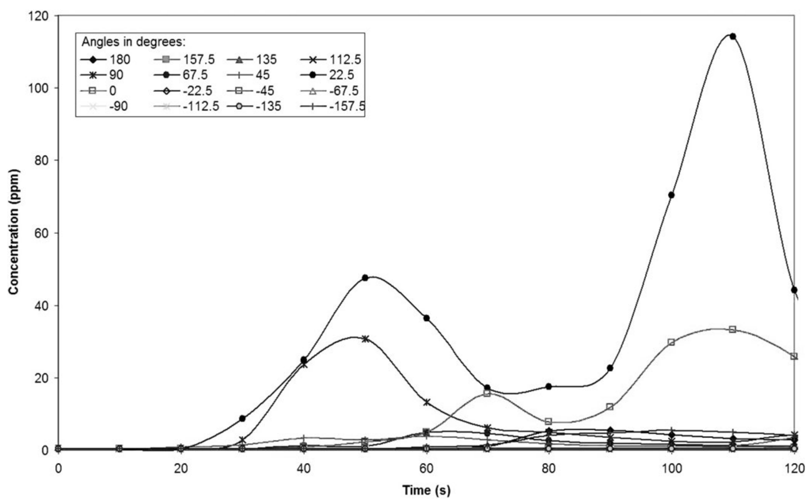

Fig. 4. Time variation of the chemical distribution measured around a chemical releaser.

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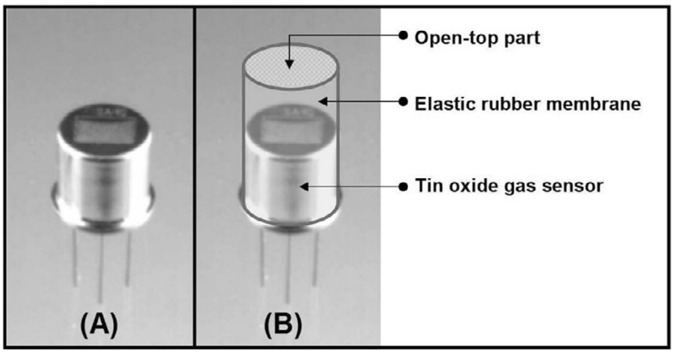

Fig. 5. A tin oxide gas sensor without and with elastic rubber membrane.

2.6. *Experimental preparation: pheromone detection*

There are a number of different kinds of chemical sensor that could have been used for this project. Metal-oxide semiconductor sensors were chosen because they are readily available, inexpensive, compact and have reasonable sensitivity. They are widely used in robotics experiments. A major disadvantage of these sensors is their slow response and even longer recovery times. This constraint has a substantial impact on the design of the robot control algorithm. Four TGS2600 tin oxide gas sensors manufactured by Figaro Engineering Inc. were mounted on each responding robot (see Fig. 3) for sensing the pheromone chemical. The TGS2600 has high sensitivity to low concentrations of reducing gases, such as methane, carbon monoxide, iso-butane, ethanol and hydrogen. Each of these sensors was wrapped in an elastic rubber membrane and the top part of the sensor was left open (see Fig. 5). This slows down their response time a little bit and lowers sensitivity but helps to reduce the pheromone fluctuation during the pheromone pulsing processes.[48] Figure 6 shows the sensor response with and without the elastic rubber membrane. In this experiment, pairs of chemical sensors were mounted close to each other, one with and one without the elastic rubber membrane. The recordings from one pair of sensors (right-hand panel) were made 5 cm from the chemical source compared to the recordings from three pairs of sensors (left-hand panel) arranged 20 cm from the source. The chemical pulses were then released for 60 and 10 s, respectively, for the left and the right panels. Shaded areas on the graphs indicate periods where the robot released a chemical pulse. It can be seen that using the elastic rubber membrane reduced fluctuations in the sensor response.

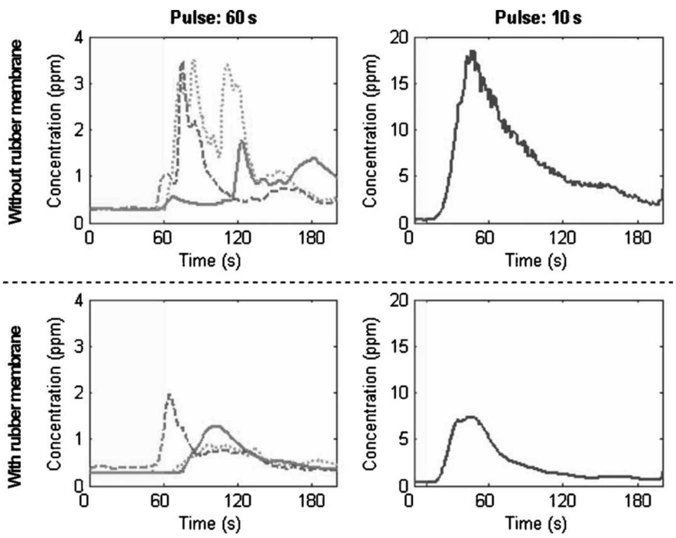

Fig. 6. The sensor response without and with elastic rubber membrane.

Over a limited range of chemical concentration, the response of the TGS2600 can be approximated by using the following relationship[49]:

$$R \approx R_0 K C^{\alpha}, \quad (1)$$

where C is the concentration of the pheromone chemical, R is the sensor resistance on exposure to the pheromone chemical, R_0 is the sensor resistance in clean air, K is the response coefficient for a particular chemical and type of sensor and α is the sensitivity. This relationship was used to convert sensor readings to chemical concentration in parts per million. Based on the previous estimates calculated by Russell,[14] the values of $K = 0.67$ and $\alpha = -0.31$ were assumed. In addition, the value of the sensor resistance in clean air R_0 for each robot was initialised at the start of each experiment.

3. Sensor Data Processing and Robot Control Algorithm

The reliable detection of a pheromone signal by a responding robot is made difficult by the patchy nature of the pheromone transmission in air and the slow response and even longer recovery time of tin oxide gas sensors. These problems affect many projects that involve robots responding to volatile chemicals. There are several possible approaches for implementing group size estimation using pheromone communication. However, the non-ideal characteristics of chemical transmission and detection must be taken into account when deciding upon an approach. A number of possible techniques for implementing quorum sensing have been considered. Firstly, each robot releaser could broadcast a different pheromone chemical and each robot receiver would require an electronic nose that could differentiate those chemicals, identify the releaser and hence determine the group size. However, this idea would be very expensive to implement both for the production and detection sites. It is also very hard to find the necessary number of suitable environmentally friendly chemicals and associated sensors. In addition, determining the individual pheromone chemical components in a mixture would require a complicated pattern recognition system. The next idea was to take the summation of pheromone concentrations received from each robot releaser. The expected result was that the quantity of pheromone detected would increase linearly with the number of releaser robots. Unfortunately, because of the highly fluctuating concentration of chemicals carried by airflow it was not possible to obtain a reliable indication of robot numbers based purely on concentration. Further, it proved very difficult to reproduce the same pheromone chemical pattern each time an experiment was run. The final idea and the one selected are based on using pulses of pheromone.

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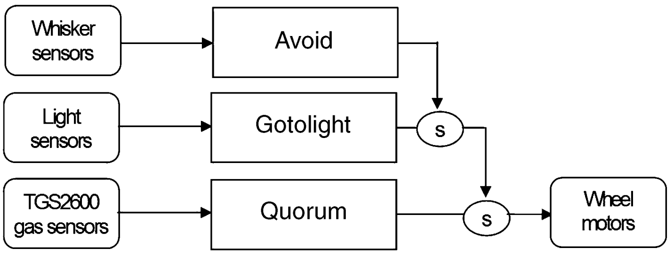

Fig. 7. A diagram illustrating the main control scheme for the responding robots drawn in the style of Rodney Brooks subsumption architecture.

Each robot emits pheromone pulses at the same rate. When not sending a pulse the robot monitors its surroundings for pulses from other robots. When the detected pulse rate exceeds a threshold the quorum has been achieved. The use of pulses rather than concentration level helps to overcome the fluctuations in chemical concentration. If chemical concentration is used to assess the number of robots in a group then variations in the amount of chemical received will directly affect the result and make it unreliable. The detection of chemical pulses is much less subject to misinterpretation due to variations in the average chemical concentration. Pulses can still be detected even when there is significant variation in the overall amplitude of the chemical signal.

For each robot the main control algorithm performs the operations of releasing chemical, sensing and waiting (relating to generating the pheromone signal and the quorum-detection process), seeking the light source and avoiding obstacles. An initial cleansing process was also undertaken before the start of each experiment for stabilising the tin oxide gas sensor. Figure 7 illustrates the main control scheme of the responding robots in the style of the subsumption architecture.[50,51] There are three main behaviours: quorum, gotolight and avoid. In theory, the main algorithm is simple; each robot has information about the required quorum size. In order to detect that a quorum had formed, each robot released pheromone pulses and at the same time sensed pheromone pulses arriving at the robot over a certain period of time. The number of pulses is proportional to the group size. When the required group size was detected, this condition triggered the light-seeking task (gotolight behaviour) as well as avoiding obstacles (avoid behaviour). However, the implementation was much more difficult than what appears on the surface. An ideal pheromone pulse would be produced uniformly around the outer edge of the robot and then propagate outwards equally in all directions with an amplitude falling off with distance. Environmental conditions and possibly also the mechanism for emitting pheromone pulses resulted in large variations in chemical concentration at different points around each robot. A series of experiments was therefore performed to help develop and improve the simple control algorithm so that it could accommodate the characteristics of the pheromone signals and the sensors.

Figure 8 illustrates the process of releasing pheromone pulses from three robots. Each robot has a different total period of releasing and sensing (T1, T2 and T3) and there is a variation in their start times. Ideally these diverse periods have to be organised to eliminate overlap in pheromone signals. Besides this, a pheromone pulse cannot be produced and detected as perfectly as shown in Fig. 8. Experimentally observed pheromone pulses are given in Fig. 9. In this figure a robot releases pheromone pulses with intervals of 5, 10 and 15 s (the top panel). The shaded regions in the graphs represent the time of release of the pheromone. The curves show the responses of the four sensors mounted on the robot releaser. It can be seen from the graphs that the sensors do not respond instantaneously. This is mainly caused by the propagation time of the pheromone pulse through the environment and the response time of the sensors themselves. The bottom graphs show sensors responses on a receiver robot adjacent to the releaser. In this case, the propagation time is even longer. Moreover, the lengths of the pulses recorded by each sensor are very variable and the pheromone pulses captured are also patchy. Additionally, as can be seen from the same figure, the recovery of a sensor to its original value (clean air condition) takes several times longer than the original onset response. As a result, the width of a received pulse is normally longer than the duration of the transmitted pulse itself. The width of a 10-s transmitted pulse became approximately 60 s at the receiver. Therefore, in order for individual pulses to be discriminated with N responding robots, each robot would release pheromone pulses on average every T seconds, where

$$T = 60N. \tag{2}$$

The strength of a pheromone pulse is a paramount concern in providing a detectable signal. This depends on the release duration and the flow rate of the pheromone source. Experiments were conducted with chemical releaser flow rates varying between 1 and 2 l/min. A flow rate of 1.5 l/min was chosen as a suitable value for this application. Greater flow rates were seen to result in a longer recovery time for the sensor. Several experiments were conducted to investigate pulse duration. In these experiments, pulses of 5, 10, 15, 30 and 60 s were generated. As can be seen in Fig. 9, the longer the pulse, the higher the concentration of a pheromone in the region surrounding the robot and the wider the region in

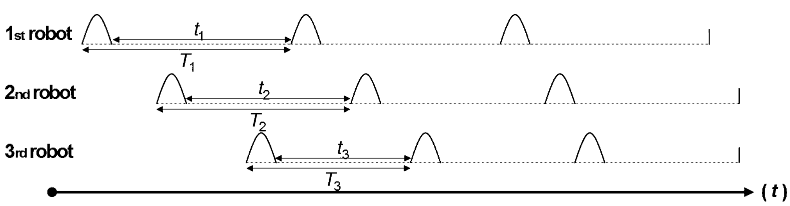

Fig. 8. Pheromone pulses released by each of the three robots.

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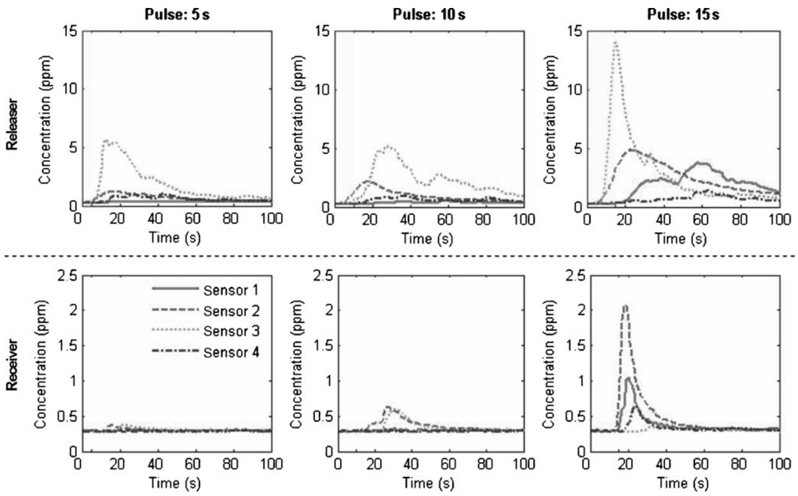

Fig. 9. The effect of chemical pulse duration on chemical concentration detected by the releasing robot (top row) and an adjacent receiving robot (bottom row). The shaded region of each of the releaser graphs corresponds to the period during which the chemical pulse was emitted. For each of the three sets of data the upper and lower graphs have the same time scale.

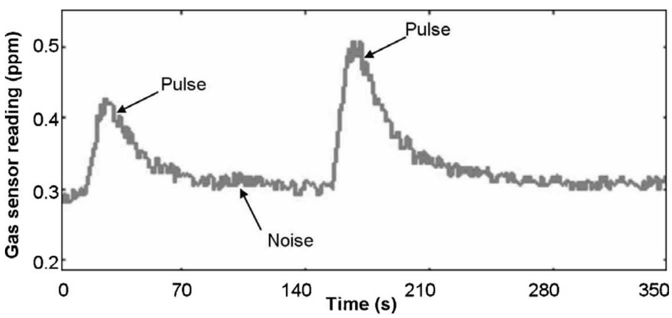

Fig. 10. Pheromone signals.

which it will be detected. However, the higher concentration of pheromone results in a longer recovery time for the sensor. After analysing the response pattern of the sensor, 10 s was chosen as a reasonable duration for a pulse. The active space region in which a robot receiver could detect the 10-s pulse was found to extend about 37 cm from the centre of the releasing robot.

The detection of a pulse not originating from the receiving robot indicates the presence of another robot close by. When a pheromone pulse is received by a robot, the desired signal will always be associated with some random noise (Fig. 10). Pulses with large amounts of added noise are difficult to recognise automatically. To help to create more easily recognised pulses, hardware and software modifications were implemented. As explained in Section 2 (Figs. 5 and 6), a rubber membrane around the sensor improved pulse shape. In addition, an algorithm was developed for detecting the presence of pheromone pulses. A scaling amplitude ratio was used to help distinguish an informative signal from noise. In these experiments the scaling amplitude ratio (R) was given a value of 0.25. In order to recognise a pheromone pulse as distinct from noise, an amplitude signal A (the difference between maximum and minimum) has to be equal or greater than the maximum signal L_{max} multiplied by R.

$$A \geq RL_{\max}. \quad (3)$$

After a robot recognises that the target group size has been reached, it then waits for a certain period of time, to allow the other gathered robots to recognise the quorum. While in the waiting period, the robot must still release pheromone pulses indicating its presence to other neighbouring robots. The length of the waiting period W was chosen to be at least double the maximum pulse transmission period T_{max} (see Fig. 8).

$$W \geq 2T_{\max}, \quad (4)$$

where T_{max} is the maximum period between pheromone pulses.

When a robot establishes that the target group size has been reached, this robot helps other robots in the group to come to the same conclusion by doubling its own pulse rate while in the waiting period. This self-reinforcing behaviour helps to ensure that all members of the group recognise that the target size has been achieved. In this application, achieving a quorum triggers the execution of a light-seeking behaviour where the group home in on a light using their light sensors. It could be assumed that the light marks the location of a task requiring the combined attention of the group of robots.

4. Experimental Results and Discussion

The starting point for the experiments was a group of responding robots gathered round a robot leader. A different chemical signal was assumed to have triggered this congregation behaviour as outlined in Section 2 and shown in Fig. 1. Note that the robot leader is responsible for gathering together the group of responding robots but it does not take part in the following group activity. The laboratory was in darkness during the experiments except for the light source marking the target position for the responding robots. The responding robots gathered in the congregation area and then monitored the group size. When a quorum was reached, these robots moved to the light source.

The sequence of graphs in Fig. 11 show data gathered from three robots during one experiment. In this experiment,

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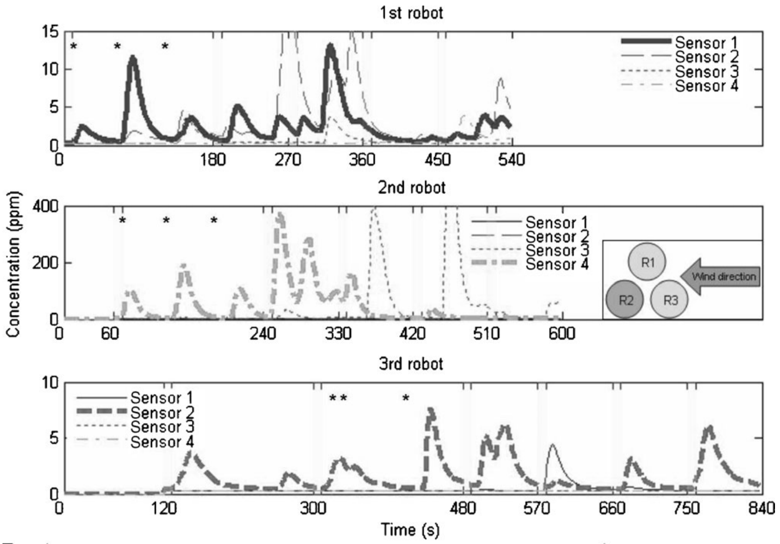

Fig. 11. Graphs illustrating pheromone pulses released and sensed by three robots.

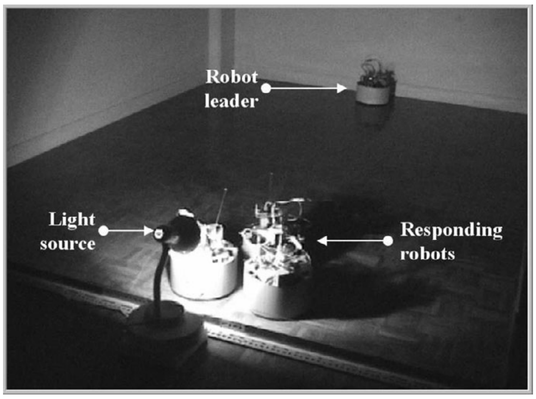

Fig. 12. When the quorum is reached, it triggers the group of responding robots to leave the congregation area around the robot leader and to move to the light.

Table I. Success rates for the quorum experiments.

	Experiments			
	Success			
Number of responding robots	Success	Mean (min)	Standard deviation (min)	Failure
2	7	10.1	1.2	3
3	11	13.8	2.2	4

three responding robots successfully used pheromone communication to gauge group size. Each robot in the congregation area emitted pheromone pulses (methylated spirits vapour) and monitored pulses from the other robots. In this case, the time period T used for each robot was 3 min, but the starting time was different for each robot. The shaded areas on the graphs show the times when the robot released pulses. The four different curves on each graph represent pheromone signals captured by the four sensors on each robot. Peaks marked with a star '*' represent recognition of a chemical pulse by the robot. This information is used to recognise that a quorum is present. After the quorum is recognised, the robot enters the waiting period and increases its pulse rate. After reaching a quorum, the responding robots move to the light source (Fig. 12). Using this quorum process the robots successfully released, detected and interpreted the pheromone signals and then changed their activity. Note that the position of the second robot in this experiment was down wind from the other two (see the inset diagram showing the robots' position in the second graph of Fig. 11) and this resulted in the second robot detecting a higher chemical concentration level compared to the other two robots. The airflow was the result of naturally occurring air currents in the room and not due to any fan or ventilation system.

In this project a total of 10 experiments with two responding robots and 15 experiments with three robots were performed. The success rates were 70% and 73%, respectively. A statistical summary of the experiments is given in Table I and Fig. 13. Table I shows the number of experiments run for two different quorum sizes and the number of successes and failures. The histograms and the box-plots reported in Fig. 13 illustrate statistical data from the successful experiments. The curve on each histogram represents the distribution fit of the histogram. The horizontal axis of the each histogram is the duration of the experiments and the vertical axis is the frequency of successful experiments. These diagrams assess the sample distributions of task completion times for two and three responding robots. It can be seen from the table and figure that completion time tends to increase as the size of quorum increases. The average times to complete the task using two and three robots were 10.1 and 13.8 min, respectively.

The sensor data processing algorithm was developed by careful consideration of the physical situation and sensor characteristics. However, some unexpected problems still occurred. Experimental failures were mainly caused by two major problems. First, even though the experiments were run in an indoor laboratory with only very minor ambient air movement there were still sudden changes in direction of

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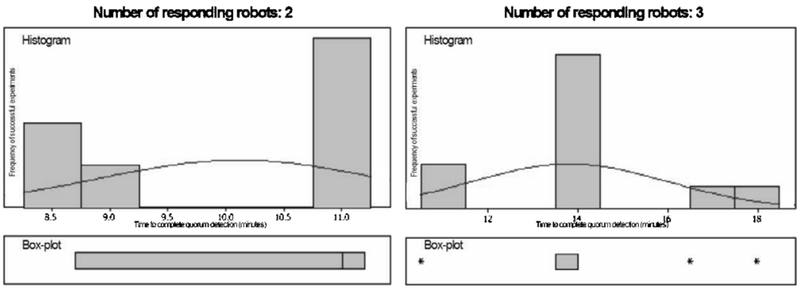

Fig. 13. Statistical summary of successful experiments.

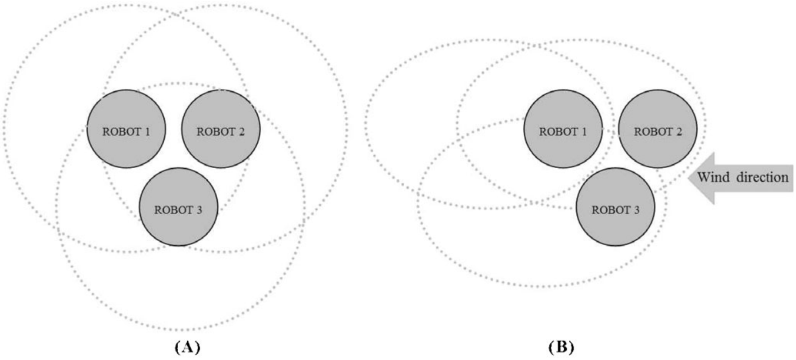

Fig. 14. The active space region is influenced by the wind direction in the experimental arena.

air movement in the experimental arena. In the other words, currents of air were not reliable in terms of flow rate and direction. This situation affected the active space region. Basically, the active space cannot be maintained perfectly, as detailed in Fig. 14(A). In each experiment, the responding robots were positioned and expected to be in the active spaces region of each other. However, the real conditions while running the experiments were unpredictable. Fig. 14(B) illustrates that when the airflow is coming from a certain direction, it changes the active space region. In this case, the effect is that ROBOT 2 might not sense the pheromone signal from ROBOT 1 and ROBOT 3. The result is that ROBOT 1 and ROBOT 3 recognise that congregation is complete and stop releasing pheromone signals, ROBOT 2 then fails to detect them. In his fascinating paper on olfactory sensing, Settles[52] explains the importance of considering fluid dynamics for the effective collection of olfactory trace signals. It may be that there are fluid dynamic effects that can be employed to create a chemical distribution around the releaser that is closer to the desired form.

Next, the shape of the pheromone signals can cause a longer experimental duration and faulty recognition of a pulse. As can be seen in Fig. 15, when the number of pulses within a certain period of time is increased this can cause pulses overlapping. In these graphs, the shaded regions represent the time of release of the pheromone by a robot releaser. The curves on the top and bottom graphs show the responses of the four sensors mounted on the robot releaser and receiver robot, respectively. If there are two pheromone pulses in less than a 30-s period, there is a high possibility of overlapping and the pulses being counted as a single pulse. This overlap would be particularly significant if the receiving robot's own pulse coincided with the arrival of a pulse from an adjacent robot and hence

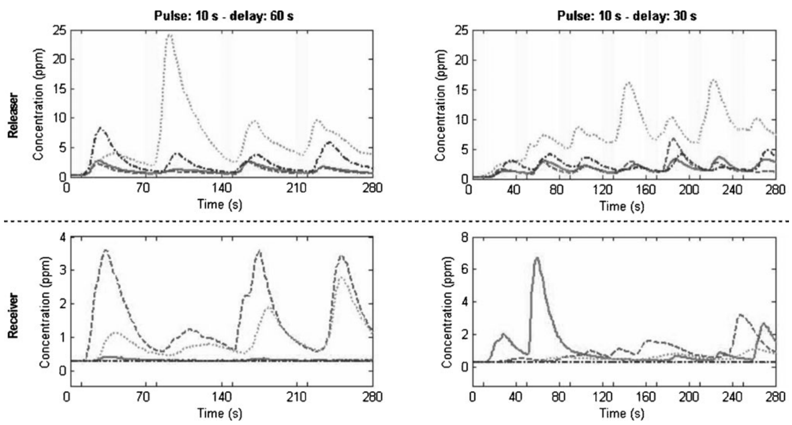

Fig. 15. The effect of increasing the number of pheromone pulses in a certain period of time.

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masked the arrival of the adjacent robot's pulse. In another words, two pheromone pulses released by two releaser robots are counted as a single pulse released by a single releaser robot. These phenomena result in delaying of the quorum-sensing process and this corresponds to a longer experimental duration. To solve this problem the scaling amplitude ratio was set quite low and thus it can detect pheromone signals in low pheromone concentrations (± 0.4 ppm) or in closely overlapping conditions. This algorithm works very well and rejects small amounts of noise. However, large amounts of noise have been incorrectly identified as a pulse. Another problem can be seen in Fig. 11. The chemical distribution surrounding the releaser measured by the four sensors is not distributed evenly. Some sensors detect a weaker chemical concentration level and under these conditions it would be quite easy to confuse a single pulse as multiple pulses. This phenomenon can lead to incorrect counting of the pulses. Stronger pulses resulting in a higher concentration of chemical can be used to solve this problem; however 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. Fluctuations in chemical concentration are an effect of the size of the experimental area. If the robotic systems were miniaturised it could be expected that concentration fluctuations would become less of a problem.

With regard to the issue of scalability, the use of chemical pheromone pulses to determine the group size has some drawbacks. As explained previously, the use of pheromone pulses requires a sufficient time interval between pulses from different robots in order for a receiver robot to let them apart. This would imply that for a larger number of robots, the interval between pulses may have to be quite long. This drawback can be reduced with the improvements in sensing technology that increase the speed of sensor response and thus the length of the pulses can be reduced significantly.

5. Conclusions

Pheromone communication for robots has a number of potential advantages that are not available from other alternative signals. Plumes of pheromone chemical provide an invisible guide path between the releasing and the receiving robots. Such pheromone communication is invisible, immune to electromagnetic interference and can propagate through convoluted pathways that would block light wave or wireless propagation. All communication channels can be swamped by external noise or blocked by a particular screen or absorber. In clandestine situations it may be known that the opposition is monitoring certain forms of communication. In these situations an alternative form of communication, such as via chemical signals, may provide a viable communication channel where others cannot be used.

This project has demonstrated bi-directional pheromone communication between robots. However, the speed and reliability of communication need significant improvement for practical applications. Significant problems were encountered in terms of fluctuations in the strength of the chemical signal caused by turbulence in the air carrying the chemical. The characteristics of the available chemical sensors in terms of speed of response and sensitivity provided additional challenges.

In order to address practical applications robotic pheromone communication needs vastly improved chemical sensors. Sensitivity and speed of response must be increased by many orders of magnitude bringing them into line with the known characteristics of equivalent biological sensor. In order to function in chemically complex environments better sensor selectivity is also required. Some of the problems associated with fluctuating airflow between robots can be addressed by paying more attention to understanding and controlling airflow.[52]

With improvements in sensing techniques and data processing algorithms applications for robotic pheromone communication will develop. These applications will appear in some of the environments (liquid/gas) and at some of the size scales (bacterium to elephant) where other communication technologies cannot be applied.

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