Robot Communication via Substrate Vibrations

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Abstract

This paper reports on a project to develop a form of inter-robot communication using substrate vibrations. Several species of insects and animals create vibrations in the surface they are standing on in order to transmit information to conspecifics. This form of communication has a number of advantages not shared by some other methods. It ensures that the message is only received by creatures that share the same substrate. If mobility is restricted to moving over the surface of the substrate it ensures that there is a reasonable chance of finding a navigable path from the receiver to the originator of the vibrations. Vibration communication could also be used in situations where wireless or optical communication were not possible due to the screening effect of nearby metal structures or in situations where it was undesirable. In this project a fixed vibration generator has been developed together with a detection system mounted on a mobile robot. Signal processing algorithms were developed to identify two different transmitted messages and provide amplitude information that could be used to guide the mobile robot towards the transmitter. This paper provides details of the vibration transmitter, the receiver, signal processing algorithms and robot control algorithm. Practical results of vibration communication where different mesages are passed between transmitter and receiver together with source location experiments are also given.

1 Introduction

Inter-robot communication is important in those situations where a large group of robots are combining together to complete a task. Communication allows coordination so that multiple robots can cooperate while being geographically spread out. It can also be used as a call for attention to gather robots in a specific location for some concerted action such as a rescue operation. Insects and particularly social insects are a good guide to what is possible in these areas.

With technological creatures such as robots there is a tendency to limit consideration to radio or optical signalling. However, other forms of communication can provide unique advantages. In this project the possibilities of transferring information via ground vibrations is being considered. Insects are one example of creatures that communicate via substrate vibrations [Cokl and Virant-Doberlet , 2003], [Barth, 1982], [Roces, and Hölldobler, 1995]. Ground vibrations are particularly useful because they limit interaction to individuals that share the same physical substrate. For terrestrial creatures that must walk/crawl/roll/etc. in order to meet up this automatically eliminates signals from regions where there is no connecting substrate.

For insects vibrational communication is not restricted to conspecifics. Scorpions and other hunting insects use ground substrate vibration to locate their prey [Barth, 1982]. In an earlier project a robot was developed that could move towards the source of an impulse caused by knocking on a wooden substrate [Wallander, Russell, and Hyyppä, 2000]. However, in the project the aim is to investigate the possibility of using substrate vibrations to communicate between robots. The aim was to transmit small amounts of information between robots and to use substrate vibrations to allow one robot to find another based on the emission of a substrate vibration. These kinds of capabilities could be used to communicate within damaged structures and to call for assistance.

2 Vibration Transmitter and Receiver

Two methods, impact and continuous oscillation, were considered for coupling vibrations into the robot's substrate. In the insect world there are examples of both of these modes of generating vibrations. For instance, the courting male *Cupiennius* spider induces vibrations into the substrate by oscillating its abdomen [Barth 1981]. By contrast the deathwatch beetle produces its characteristic sound by impacting its body onto the wooden substrate. In order to produce a distinct but relatively unintrusive signal it was decided to experiment with a vibratory signal produced by continuous vibration. By changing modulation of the vibration it would be possible to send different messages. To generate this signal a small d.c. motor was fitted with an offset weight. Speed of rotation was controlled by varying power to the motor by pulse-width modulation of the supply voltage and monitoring the resulting rotation of the motor using an optical switch. The vibration generator was controlled by its own C167

microcontroller board. A photograph of the vibration generator is shown in Figure 1.

Figure 1 The computer-controlled vibration generator.

The intention was that a mobile robot would carry a vibration receiver. Considering substrate vibrations it appears that waves travelling through the body of the substrate attenuate quicker than those at the surface. Rayleigh waves are surface waves that produce vertical motion and it was decided to build a detector for these waves because such a detector would have a sensitivity that falls off slowly with distance and be largely non-directional. The ADXL202JE integrated accelerometer was chosen to detect the vibrations. A radio control servo pressed the accelerometer assembly (Figure 2) to the substrate when monitoring vibrations. Springs were used to provide mechanical isolation this assembly from the body of the robot.

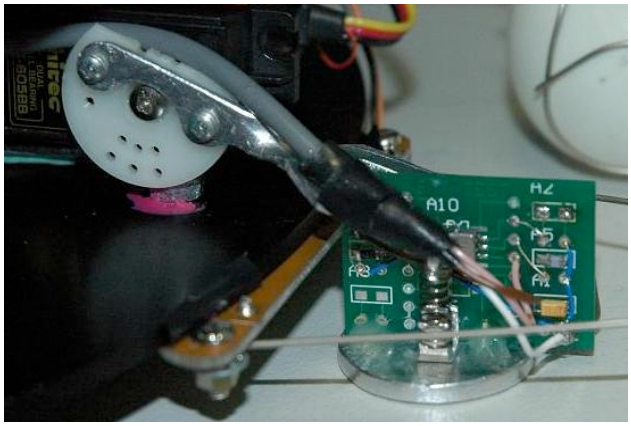

Figure 2 The accelerometer assembly.

The ADXL202JE contains two accelerometers but only one of these was used in this experiment. Output from the accelerometer is in the form of a variable mark-space ratio pulse and this was monitored using one of the timer inputs of the robot's microcontroller (Figure 3).

3 Vibration Communication

It was decided to use a vibratory signal that sweeps through a range of frequencies To be useful for robotic communication the requirement is for one or more identifiable signals that can be generated and detected. If several different signals can be communicated then there is the possibility of increasing the quantity of information that can be communicated.

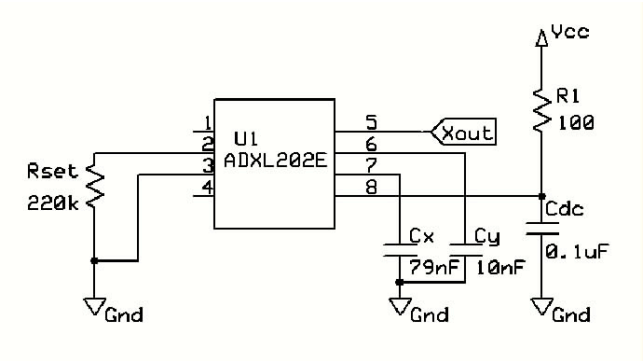

Figure 3 The accelerometer schematic.

After experimenting with the vibration generator and taking into account its limitations it was decided to transmit two different signals. The type 1 signal was to be formed by sweeping the vibration generator frequency between 50-60Hz and type 2 with a frequency range 37.5-60Hz. The form of these two signals was partly dictated by the fact that the vibration generator cannot be instantaneously switched to a different frequency.

In order to detect the transmitted signals we decided to use a matched filter. For this it is necessary to calculate the cross correlation between the actual signal received and the expected signal. The cross correlation of periodic sequences is calculated using:

$$r_{xy}(l) = \frac{1}{N}\sum_{n=0}^{N-1} x(n)y(n-l) \qquad (1)$$

where:

x(n) and y(n) are two periodic signals,
l = a time shift parameter, and
N = sequence length.

In our case this is modified because of the different sizes of the two sequences and removing the requirement to perform division on the robot's microcontroller:

$$r_{xy}(l) = \sum_{n=0}^{N+M-1} x(n)y(n+k-l) \qquad (2)$$

where:

x(n) = the accelerometer signal, and
y(n) = a preprogrammed filter signal.

In this project M = 1300, N = 200 and k = 199.

After experimenting with various forms of signal, some generated in Matlab and others measured experimentally, best results were obtained using the recorded sequence shown in Figure 4 as the preprogrammed filter signal.

For both type 1 and type 2 signals there is a segment of the chirp with a frequency range 55-60-55 Hz. The difference is in the spacing between these segments. Figure 5 shows the cross-correlation for a type 1 signal and the time difference between peak values occurs within

a widow of 600ms ± 75ms.

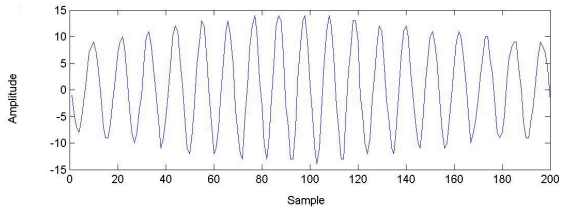

Figure 4 A symmetric filter signal with frequency range 55-60-55 Hz.

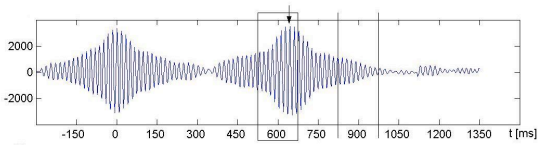

Figure 5 Detecting a type 1 signal.

When receiving a type 2 signal the expected time between peaks is 900ms ± 75ms and an example of a type 2 signal is shown in Figure 6.

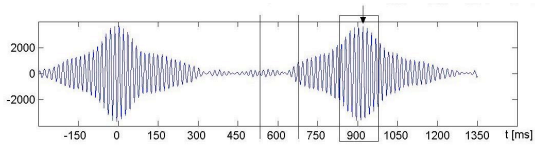

Figure 6 Response to a type 2 signal.

Thus, the time difference between peaks in the cross-correlation is used to identify type 1 and 2 signals. The correlation technique rejects noise and erroneous signals that produce cross-correlations below the detection threshold.

4 Vibration Source Location Algorithm

4.1 The characteristics of substrate vibrations

Having built a vibration transmitter and mobile robot equipped with a receiver together with signal detection software the next stage of the project was to map out vibration amplitude on a sample substrate. The substrate shown in Figure 7 is a sheet of chip board lying on resilient carpet tiles. The vibration generator is located in the centre of the sheet and is held in place by a 1.5 kg weight simulating the weight of a robot carrying the generator.

By programming the robot to take vibration measurements at regular intervals over the surface of the experimental substrate images of vibration amplitude were created. Figure 8 shows the distribution of vibration amplitude with the vibration generator positioned at the centre of the substrate.

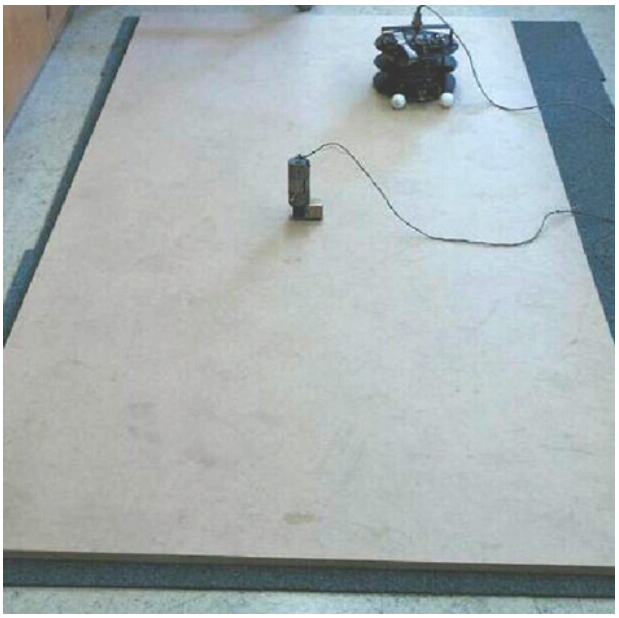

Figure 7 The experimental substrate.

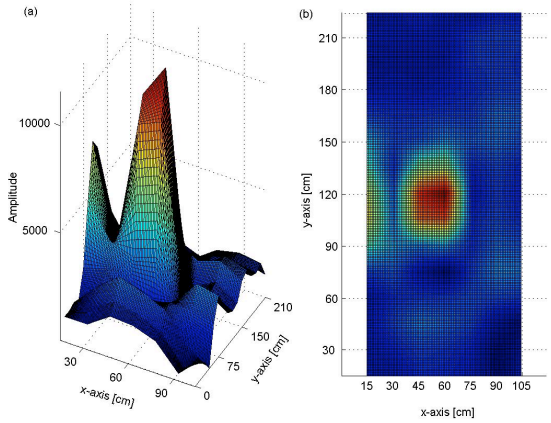

Figure 8 The distribution of vibration amplitude over the experimental substrate.

It can be seen that there are many local maxima in the distribution of vibration amplitude. The amplitude only rises in a consistent manner very close to the source. These characteristics of the vibration signal were taken into account when designing a source location algorithm.

4.2 The spiral search algorithm

In some ways the fluctuating amplitude of the substrate vibrations bears a resemblance to the fluctuating concentration in a chemical plume. For this reason odour plume tracking algorithms were surveyed. The spiral surge search algorithm described by Hayes, Martinoli and Goodman [2003] seemed to contain some useful ideas. However, the algorithm was not directly applicable because the substrate vibrations do not have any feature that matches the flow direction of odour plumes.

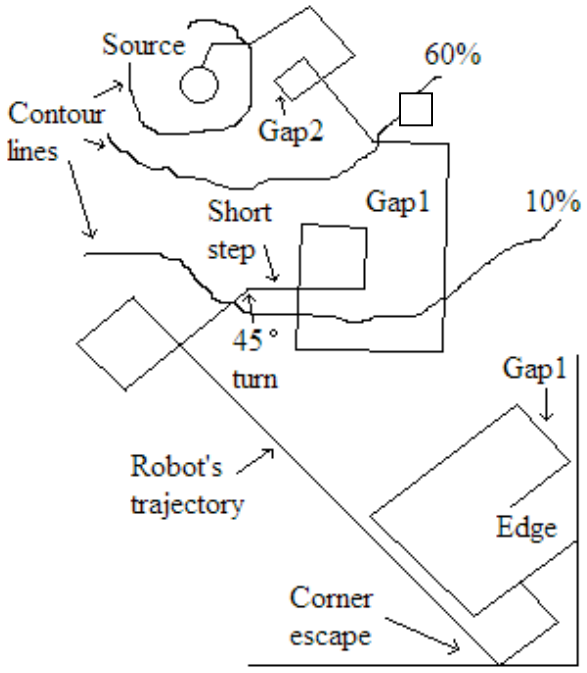

Figure 9 Spiral search algorithm.

After experimenting with a number of different variations the following algorithm proved effective. The initial search is conducted using a square spiral path with a spacing between successive turns of the spiral of 20 cm (gap 1). A larger initial gap would reduce the number of measurements needed and would be more efficient. However, due to the comparatively small arena a narrow gap was used to avoid frequent collisions with edges of the substrate. Spiralling with the 20 cm gap involves taking a sample every 20 cm and making turns in a counter clockwise direction. The initial spiral is continued until the threshold amplitude of 10% of the expected maximum value is exceeded. This is done because the robot is able to receive vibrations throughout the arena. When the threshold amplitude is exceeded the robot saves this amplitude as the largest amplitude found so far, turns 45 degrees away from the direction it was heading and continues taking samples 13 cm apart. If the new value is at least 10% larger than the earlier largest amplitude, it is saved and the robot continues straight forward taking the next sample after another 13 cm. If the new value is not large enough, a new spiral is initiated using a 20 cm gap and the procedure is continued in a similar way until the second amplitude threshold value is exceeded.

Exceeding the second amplitude threshold value changes the spiral gap to 13 cm permanently. The same procedure is carried out as with the initial search. If the new value is larger than the earlier maximum the robot turns 45 degrees from its current direction and continues straight forward until the value is not getting larger and a new spiral is initiated. Using the recorded maximum value as a reference results in the robot being able to find its way out of a local maximum, instead of getting stuck in it. The robot moves to the location of the largest amplitude and if the source is not located there it initiates a new spiral working its way slowly away from the local maxima. Recognition of the vibration source is done using collision detecting whiskers.

If the robot hits the edge of the substrate, it first turns 180 degrees, drives forward one step length, turns away from the spiral center and takes a new measurement. After measuring a new value it continues its way turning clockwise and this way spreading the spiral outwards from the edge. In some cases when the robot spirals its way near corners of arena, it gets stuck. This is due to the fact that it is always working its way outward and in the corner this is not possible. In these cases a corner escape is initiated. The robot reorients towards the edge, by turning until both edge detectors are out of the board. Then it turns 135 degree angle away from the direction it originally came from. If the maximum amplitude found is larger than the second threshold amplitude the robot is only moved a short distance from the position it got stuck and a new spiral is initiated. If the maximum value found so far is less than the second threshold value, then the distance moved is longer taking the robot further from the edge.

5. Experimental Equipment

To demonstrate the principle of vibration communication a mobile robot was equipped with the vibration sensor described in Section 2. The transmitter was built as a fixed device although it was intended that this could also be carried by a mobile robot. The mobile robot used in this project is a modified version of the laboratory robot LABOT designed at Monash University (Figure 10).

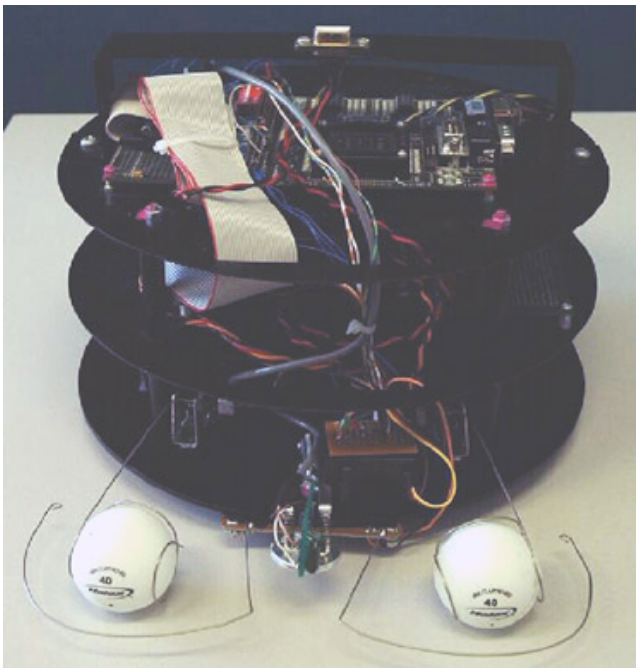

Figure 10 The LABOT robot with substrate vibration sensor together with sensors for obstacles and sudden drops.

LABOT is a 24cm diameter robot built from a stack of three aluminium disks. The lower disk carries two geared motors driving side-by-side wheels. Optical encoders attached to each wheel monitor wheel rotation. Teflon skids provide stability for the robot by making a third point of contact with the ground. The middle disk provides a mounting point for a printed circuit board containing power conditioning and interface electronics.

An Infineon C167 microcontroller controls all of the robot's systems including the vibration detection system and this is attached to the top disk. An umbilical cable provides power and a serial communications link for the robot.

5. Results

During development of the vibration source location algorithm tests were performed in simulation using the vibration amplitude measurements taken over the entire surface of the experimental substrate (Section 4.1). Figures 11 and 12 show some of the results obtained using the final source location algorithm in the robot simulation. In Figure 11 the robot was started at location (52, 23) and successfully arrived within 12cm of the centre of the source.

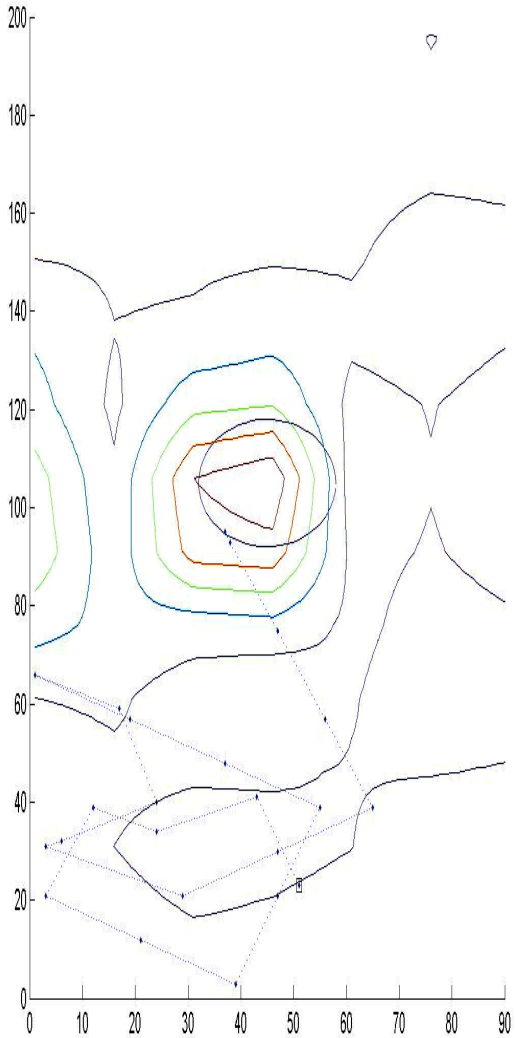

Figure 11 Success starting from location (52, 23).

When started at (73, 75) the robot became 'trapped' at one end of the substrate and failed to reach the vibration source within the allocated time.

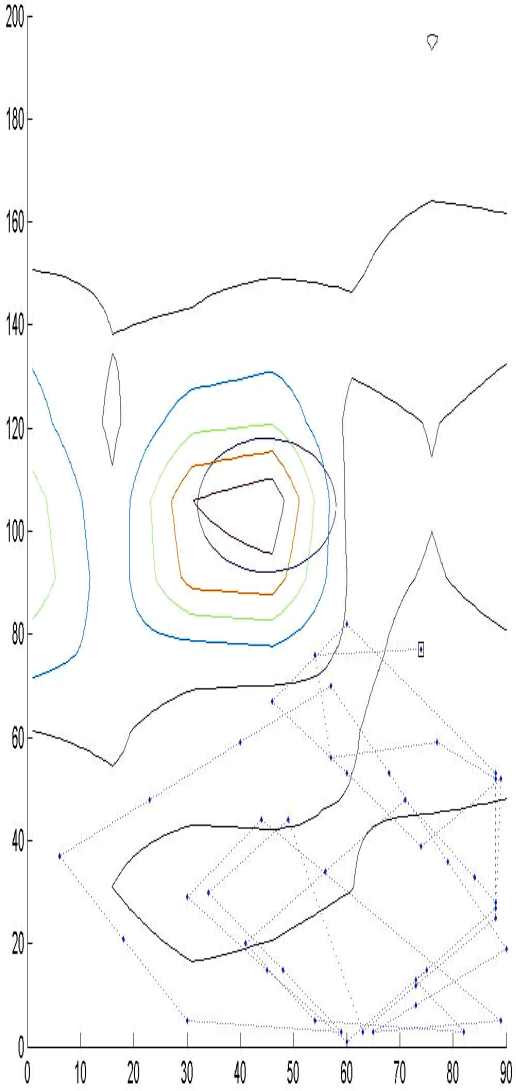

Figure 12 Failure starting from location (73, 75).

Having developed a robot control algorithm that produced reasonable results in simulation the algorithm was transferred to the physical robot. Results of practical experiments are presented in the following two tables. During these experiments the robot was programmed to react in a different manner depending on the 'type' of message it received. If the message was of type 2 the robot stoped searching and waited while monitoring the vibration signal every 5 seconds. Thus, the type 2 message was a command for the robot to 'freeze'. When receiving a type 1 signal the robot initiated the spiral search algorithm to locate the source. The type 1 message was a 'find me' command.

In the second experiment, the source was located in the corner of the board at point (30, 170). Five runs were conducted before failure of the bearings in the transmitter motor. The results from this experiment are shown in Table 2.

Table 1. Robot experimental results
(source positioned in the middle of the board)

Run	Initial position	Initial heading	Total length	Note
1	30, 40	170	321	Successful
2	90, 50	150	-	Fail, robot got stuck on the cable
3	90, 50	150	382	Successful
4	40, 180	30	-	Fail, transmitter failed to operate
5	60, 160	45	122	Successful
6	80, 60	330	170	Successful
7	95, 215	225	353	Successful, found by accident, during corner escape
8	90, 120	300	552	Successful
9	90, 120	250	206	Successful

Table 2. Robot experiment results
(source positioned in the corner of the board)

Run	Initial position	Initial heading	Total length	Note
1	70, 90	30	632	Successful
2	100, 170	70	411	Fail, robot got stuck on the cable
2	100, 170	70	411	Successful
3	85, 30	150	1305	Fail, run too long
4	20, 140	130	564	Successful
5	60, 60	45	-	Transmitter failure

6. Conclusions

If large numbers of robot are used to perform a task as a robot swarm then they will usually need to be able to communicate with each other in order to operate effectively. There will never be one form of inter-robot communication that is applicable to all types and sizes of robot in every situation where they will be used. The motivation for this project was to investigate substrate vibration that is one communication technique employed by a number of different creatures, particularly insects. A substrate vibration transmitter and receiver have both been developed and the receiver mounted on a small mobile robot. Programmes have been written for the robot's C167 microcontroller to detect and discriminate two different vibration signals and also guide the robot towards the vibration transmitter.

In practical experiments the robot was able to respond appropriately to different signal types and to home-in on the transmitter when commanded to do so. However, there were occasions where the robot failed to locate the transmitter. Some failures resulted from equipment malfunction including getting tangled in the robot's umbilical cable. In other cases the robot could not escape from a corner of the experimental substrate before the time allocated for the experiment ran out. This indicates that improvements are required in the section of the robot's control algorithm that deals with edges of the arena. Locating the source of a vibratory signal is a difficult task. In experiments with deathwatch beetles it was found that only three out of ten males were able to locate the female in a simple laboratory experiment [Goulson, Birch and Wyatt, 1994].

The vibration transmitter broke down towards the end of the experimental investigations. Spinning a large eccentric load caused motor bearings to fail. A redesign of the transmitter is necessary to reduce the load on the motor bearings. In conclusion, this project demonstrated the viability of robot communication via substrate vibrations and indicated aspects that require further investigation.

Acknowledgments

The C167 microcontroller boards used in this project were donated by Infinion. The work described in this paper was supported by the Australian Research Council funded Centre for Perceptive and Intelligent Machines in Complex Environments.

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