Autonomous Minimalist Following In Three Dimensions: A Study with Small-Scale Dirigibles.

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Abstract: This paper reports on research that extends previous work in the area of following and flocking with two-dimensionally constrained robots, into three dimensions using physical robots with limited local sensing but without direct communication. The motivation for this work stems from an interest in the emerging field of behaviour-based robotics and collective biological systems.

1. Introduction

The principal aim of this research is to develop a set of collective minimalist following/flocking algorithms for use on a group of flying autonomous robots. A group of physical robots has been designed and constructed and is being employed to demonstrate how following and flocking in three dimensions can be achieved using simple rules. The robots employ helium balloons (blimps) and therefore have a limited payload for the propulsion, communication and localisation systems. This payload constraint has led to the development of a very small and lightweight biologically inspired robotic system. This inspiration comes from large flocks of birds that employ only local sensing and communication and do not directly communicate with all flock members. The constraints imposed on the robots therefore do not allow for sophisticated or long-range communication equipment as these would both increase the power consumption and exceed the weight limit. Therefore, this study employs local sensing and indirect communication.

2. Background

Artificial flocking using behaviour-based techniques was first demonstrated by Craig Reynolds, who created a computer simulation of creatures called ‘Boids’ [Reynolds, 1987] which behaved in a similar fashion to a real flock of birds. Since then several researchers have used behaviour-based techniques to implement flocking on physical robots using various methods [Kelly 1996, Mataric 1994]. Gulliford [1998] showed how simple following behaviour can be implemented on a group of homogenous robots using very limited local sensing and three basic behaviours. These experiments use robots that have precise control and are not adversely affected by the environment. Precise control demands sophisticated sensing and propulsion. In contrast the robot blimps we intend to use are severely constrained in their payload. The extra hardware required to implement precise control would demand significant power and carries a severe weight penalty. Specifically,

- Powerful motors for more precise control will add more weight and demand more power.

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- Higher precision sensing would require a larger sensor array, which in turn adds weight and consumes more power.
- More Infrared transmission precision and coverage again requires more power and weight.

The resultant robots can only be controlled in an imprecise and sub-optimal manner and are severely affected by perturbations in the environment. Therefore we intend to employ collective minimalist techniques [Melhuish *et al.* 1996] to find a solution to the problem. Experiments by Melhuish *et al.* have shown how groups of agents can home in and converge on a static beacon in a noisy environment using very simple rules and a single omnidirectional sensor. These minimalist techniques exploit the inherent randomness of the system to achieve the desired goal.

3. Hardware

3.1. Envelope

The physical implementation of the robot uses a lighter than air vehicle (LAV) in the form of a helium filled balloon (blimp). The blimp consists of a two-panel metalised nylon envelope 96.5cm in diameter, which once filled has the shape of a squashed sphere (figure 1). The envelope has a small non-return valve to facilitate inflation with the desired lifting gas; this valve can be opened using a tube to allow the envelope to be deflated for storage or replenishment of the gas. The volume of the envelope is approximately 0.3m^3 giving a net lifting capacity of 93g when filled with Helium/Nitrogen balloon gas, which is 98% Helium, making it much cheaper than pure Helium with a negligible difference in its lifting capacity

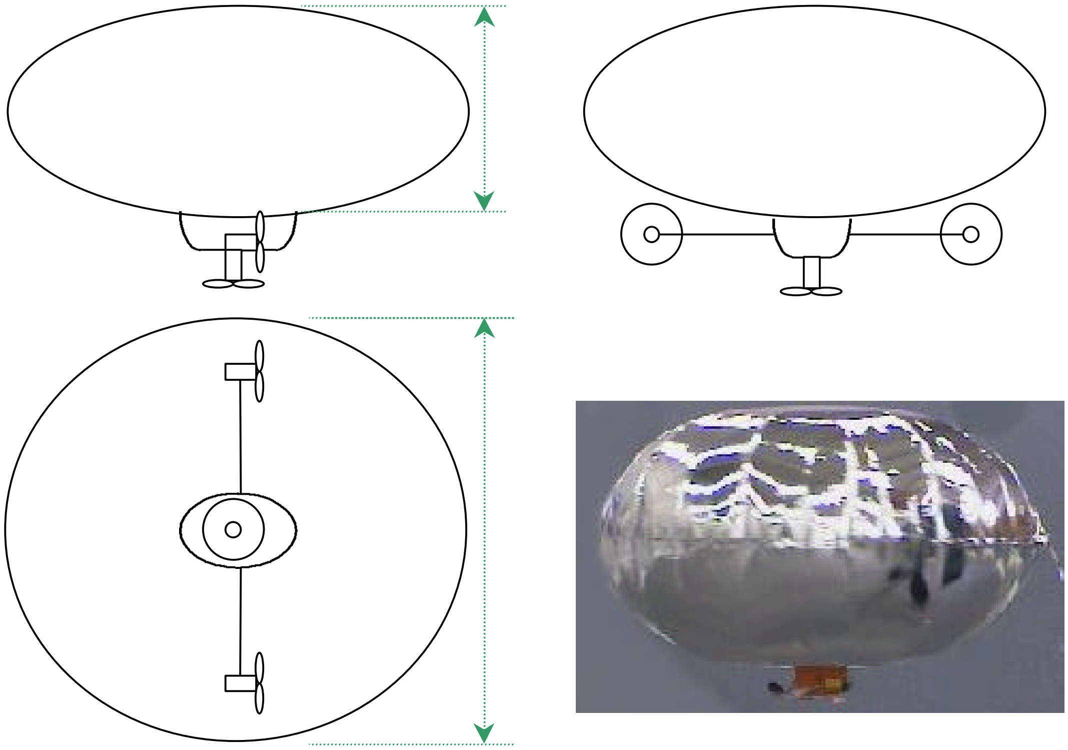

Figure 1: Physical Dimensions of the Inflated Envelope

3.2. Gondola

The blimp gondolas are made of lightweight plastic ‘blister packs’ which are commonly found holding products to a cardboard backing. Many different products are packaged this way and it was just a matter of finding something that was the right size and weight for the job at hand. The gondola is attached to the envelope with ‘Sellotape’, which is lightweight and gives a good bond that will not damage the nylon envelope when it is removed.

The final design uses the packaging from ‘Mini Jaffa Cake’ biscuits and provides enough space to hold all the electronics and batteries. The arms that hold the motors are made from plastic drinking straws (figure 2) that weigh half as much as the equivalent balsa wood structures; being plastic they exhibit passive compliance should they hit something. The plastic straws are flattened at the ends, bent around the motors and heat welded, giving a firm fixing point that requires no glue or clips. This glueless design maximises the weight saving.

3.3. Propulsion system

Thrust on the robot is achieved with three small fan units capable of supplying approximately 4g of thrust at full power. Each of these units consists of a small DC electric motor fitted with a small plastic propeller (figure 3). The motors are the same as those used for vibrating mobile phone batteries and pagers and are very lightweight (2g). The plastic propellers are 5cm in diameter and weigh 0.3g each. Each of the fans is controlled with a full bridge driver (h-bridge) to enable operation in both directions, and pulse-width modulation (PWM) to give analogue speed control.

One fan is mounted at each end of an arm to provide forward, reverse and axial rotation of the blimp. The third fan is fitted beneath the gondola to provide movement in the vertical axis. A problem with this vertical axis fan is that it will introduce a small torque, causing the blimp to rotate in the opposite direction to the propeller.

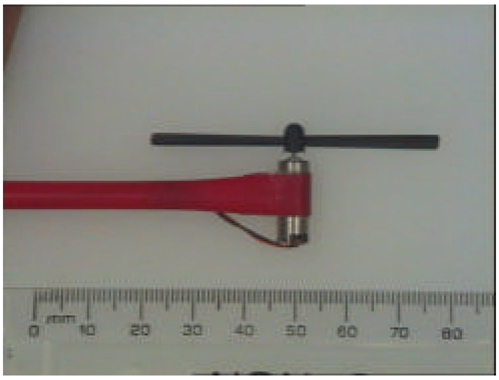

Figure 2: Motor mountings

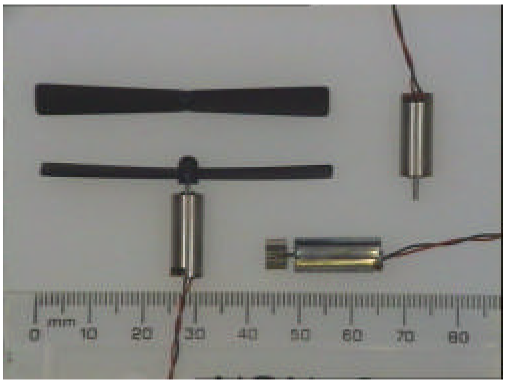

Figure 3: Motors and propellors

3.4. Electronics

The main drawback of using small blimps is the severe weight limitations placed on the design of the electronics control system: The net lift of the inflated envelope is only 93g and more than half of this (50g) is to be for batteries. All the circuits are manufactured from 0.5mm fibreglass board, which is a third the thickness of a standard circuit board. This thin board coupled with the very compact layout and the use of surface-mount technology helps to reduce the weight by a considerable amount. The major problem with such a small and compact design is that assembling it by hand is a very intricate task. The electronics are split into two distinct parts (digital and analogue) to minimise the coupling of noise from the digital board to the much more sensitive analogue boards.

3.4.1. Digital board

The digital circuit (figures 4a and 4b) has the power generation, motor drives, frequency generators and a microcontroller all of which work at high frequencies and produce a lot of noise. A step-up DC-DC switching converter and a rechargeable battery supply the 5 volts needed for the electronics. The maximum current consumed by the electronics may exceed 1Amp therefore a high current switching converter is employed. The MAX489 was chosen because it has a load capability greater than one Amp and is designed to be very low noise (4.7nv/Hz). This converter will work with an input as low as 0.8 volts, maximising the energy obtained from the batteries.

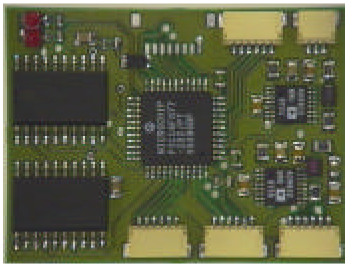

Figure 4a: Top of control board

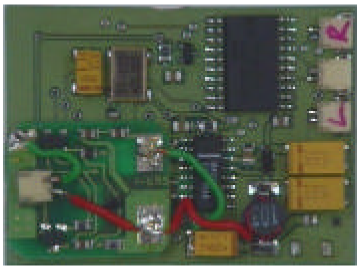

Figure 4b: Bottom of control board

(Actual size)

The motor drivers are HIP4020 full bridge drivers and are capable of delivering 500mA in an SO20 surface-mount package. These chips also feature over-temperature and over-current cut outs to prevent overheating and damage. The use of this chip helps to keep the component count to a minimum, saving weight and board space over an equivalent circuit built from discrete components.

The frequency generators used by the transmitter and receiver employ direct digital synthesis (DDS) technology to produce near perfect sine waves with minimal external components. The chips used are AD9832s, which are controlled by a three wire serial interface and come in very small (TSSOP) surface mount packages. The original design by Kelly [1996], described in the following section, used a separate crystal for each frequency, taking up valuable space and adding unnecessary weight. By replacing all the crystals with a single IC, weight, board space and cost were minimised. This new design makes it more practical to change and add new frequencies as desired using software.

The heart of the system is an 8-bit Arizona Microchip PIC 16F877 microcontroller, which runs at a frequency of 20MHz giving ample computational power. This microcontroller has 8Kbytes of onboard flash memory, which can be programmed in-circuit via a three-wire serial interface, three 8-bit digital I/O ports as well as an 8 channel analogue-to-digital (AD) converter. The unit also features two pulse-width modulation (PWM) and three timer modules.

3.4.2. Analogue Boards

There are three types of analogue board that make up the infrared localisation system: the receiver, transmitter and two sensor boards. These boards are fed from a voltage supply that has been filtered to minimise the noise induced by the high speed switching of the digital devices.

The localisation system is based on a design by Kelly [1996] which gives the relative position of and distance to the other blimps, and also allows for low bandwidth inter-blimp communications. At the centre of this design is the receiver (figure 9) which is based around a low power Phillips SA607 FM demodulator IC which has a logarithmic received signal strength indicator (RSSI). This RSSI signal is fed into an analogue to digital converter (ADC) on the control board and is used to calculate the distance to the transmitter being scanned. Each blimp transmits on a separate frequency, selected so as not to interfere with one another or any noise present in the environment. There are many sources of noise that could interfere with the infrared system especially at the frequencies being used (200KHz to 600KHz).

The infrared transmitter (figure 5) is made up of a semicircle of LEDs to give 180^0 coverage to the rear of the blimp. The LEDs used are high power 850nm infrared emitters (HIRL5015) which have a 60^0 dispersion angle. Two LEDs are placed in series and fed with a 5v sine wave at 100mA, this drive voltage is produced using high output current op-amps fed from one of the frequency generators. By using these LEDs at the stated current it is possible to achieve a range in excess of 20m which is nearly double that of Kellys original design.

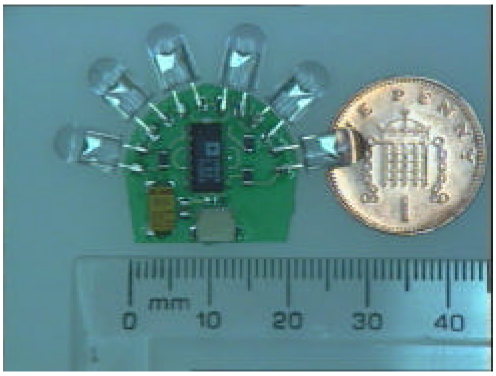

Figure 5: Transmitter Board

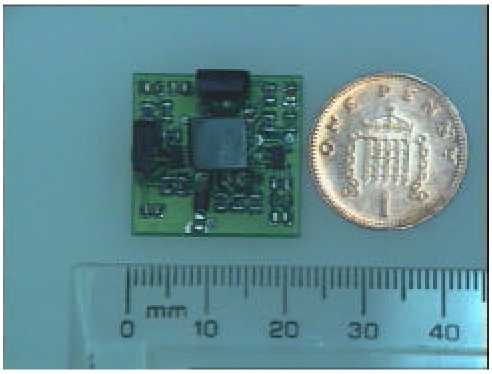

Figure 6: Sensor board

As discussed above, each blimp transmits its own unique signal so that it is possible to differentiate between the blimps. Each blimp scans all other frequencies in use except its own, as this would result in a very high RSSI signal due to the close proximity of the transmitter to the receiver.

Each blimp is fitted with three forward-facing infrared sensors (figure 6) arranged as a corner of a cube with its point facing forward to give an approximate hemispherical field of view. Each of the infrared sensors can be selected through an 8-1 analogue multiplexer, with the possibility of adding a further five sensors to expand the system if required. The position of any blimp being scanned can be calculated by correlating the data received from each sensor.

A lightweight ultrasonic ranging system has been designed which gives the robots the ability to accurately gauge their height to within a few centimetres with a maximum range of 3 to 4 metres. However, the robot cannot control its height with this sort of precision. The transmitter bounces a 40KHz ultrasonic pulse off the floor, which is picked up by the receiver to give a time of flight, which is then multiplied by the speed of sound and halved to give a distance measurement.

3.5. Batteries

Battery choice was mainly influenced by the gravimetric energy density available, the lighter the battery for a given capacity the better. It was decided to use a rechargeable (secondary) technology, because the amount of experimental run time would incur massive costs if a non-rechargeable (primary) battery technology were used. After a long search it was found that the most appropriate, easily available battery was a Li-Ion Sony Minidisc battery (LIP-12B), which gives 1500mAh at 3.6v for a weight of 50g. The internal cell itself only weighs 39g, the remainder being made up by the protection circuitry and outer casing. The weight of the battery pack was minimised by discarding the outer plastic casing which gave a weight saving of 8g. The use of this new battery gives 15-fold increase in the operational time of the robot. There is one small drawback with the new batteries in that the payload of the blimp has been pushed very close to the limit, with only a further 8g of payload that can be added. Being on the limit of the payload has several implications:

- Any further sensors to be added will require an increase in the envelope size,
- The envelope will need to be kept full of relatively pure Helium to keep them aloft. The Helium leaks out of the envelope at approximately 1% a week, given that the envelope is sealed properly, so the blimp will lose buoyancy over time.
- With an extra payload capability, ballast can be added to make the blimp neutrally buoyant, then slowly taken out as the helium seeps out, thus maintaining the neutral buoyancy without constant refilling of the envelope.

3.6. Software

The algorithms coding the behaviour of the blimps are written in the ‘C’ programming language. The use of ‘C’ makes the program development much faster and easier than writing everything in PIC assembly language. So far all the low-level control routines have been written and tested and provide a set of useful functions for the implementation of the behaviours.

4. Aggregation Experiments

Our first experiments examine the ability of the flock to aggregate and form a dynamically stable cluster. Specifically the following three experiments were conducted:

1. Aggregation on a static beacon
2. Robot aggregation without a beacon
3. Robot aggregation with a beacon

These preliminary experiments use three robots to evaluate the algorithms, which give satisfactory results without producing an excessive volume of information to process in short time. Future experiments will use more robots as this will give more reliable data and should give a better flock. The experimental arena (figure 7) is an area 12m x 12m with an overhead camera fixed 6m above the centre. The floor of the arena is made of smooth floor tiles, which give a good echo for the ultrasonic height control. The positions of the robots were recorded using the overhead camera every 10 seconds (one time step). The results are plotted using line graphs without error bars for clarity

The metrics used to analyse the data from the experiments are as follows:

- Mean distance of robots from beacon: Experiment 1
- Mean distance of robots from their centroid : Experiment 2
- Mean distance of robots from their centroid and the beacon: Experiment 3

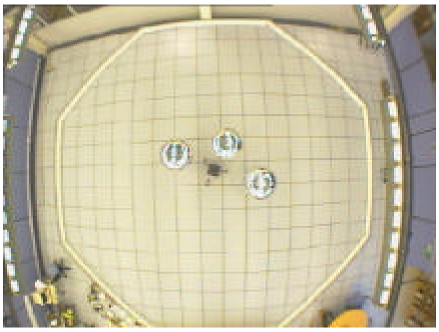

Figure 7: Overhead view of arena with IR beacon and 3 robots

4.1. Experiment One: Aggregation on a static beacon.

This experiment was used to test the ability of a group of three robots to aggregate around a static beacon placed in the centre of the arena. Each robot was given the same set of simple rules, which enabled them to home in on the beacon. The experiment was carried out three times and the results plotted in figure 8. The graph shows three separate trials of the same experiment, each of the lines gives the mean distance of all three robots from the beacon. The results of the first set of experiments show that the robots satisfactorily home on the beacon so that on average the mean distance of the three robots is not more than two robot diameters from the beacon. From the graph it can been seen that at time step 17 the mean distance increases dramatically when some robots loose the beacon only to return within two time steps. This shows that the system is dynamically stable.

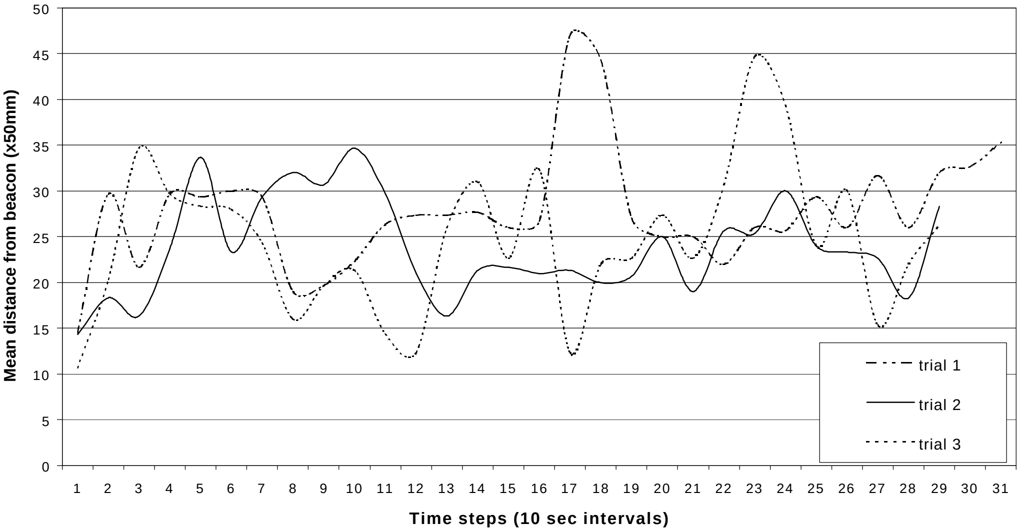

Figure 8: 3 Trials of homing on a static beacon showing mean distance to beacon

4.2. Experiment Two: Robot aggregation without a beacon.

This experiment tested the ability of the robots to aggregate and form a stable group. The rules used were the same as those in the previous experiment except the static beacon was removed and the robots own transmitter was enabled. The results from this set of experiments show the tendency for the robots to clump and stay together. The robots started in the middle of the arena touching each other. As soon as the experiments started they move apart quickly and then re-converge to maintain their separation distance. It can be seen from the graph (figure 9) that for two of the runs at time step 11 the robots break their formation and re-converge within three time steps. The clump of robots slowly drifts around the arena due three factors the air currents present in the environment, those created by the robots, and the collisions between robots. The very crude collision avoidance strategy only works for a robot approaching the rear of another robot, therefore, we are essentially not using it.

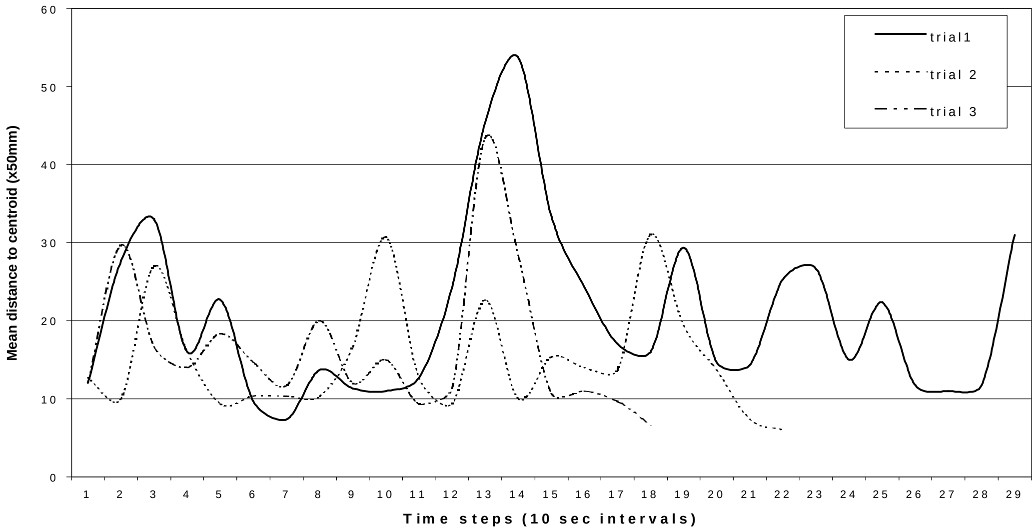

Figure 9: 3 Trials of robots homing on each other showing mean distance to centroid of robots

4.3. Experiment Three: Robot aggregation with a beacon.

The final set of experiments tested the ability of the robots to home in on the beacon whilst staying in a group. The rule set applied was the same as the previous experiments, but with both robot transmitters and beacon activated. From the results plotted in figure 10 it can be seen that the general trend is for the robots to loosely aggregate around the beacon whilst maintaining a lose group. The second run from this set of experiments shows that the robots break away from each other (figure 11) and the beacon for approximately 4 time steps. The robots then re-converge after a small time and exhibit a general stochastic drift toward the fixed beacon.

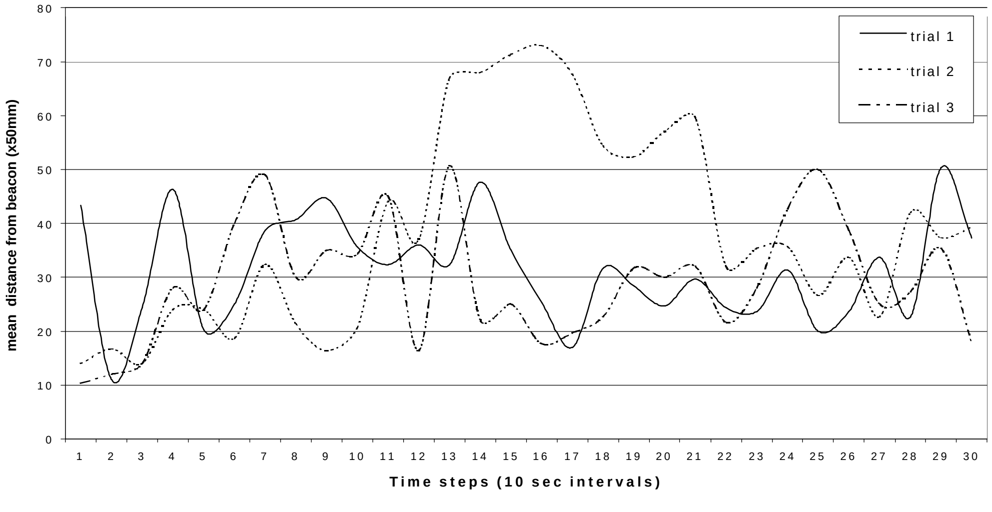

Figure 10: 3 Trials of homing on a beacon and robots Showing mean distance to beacon.

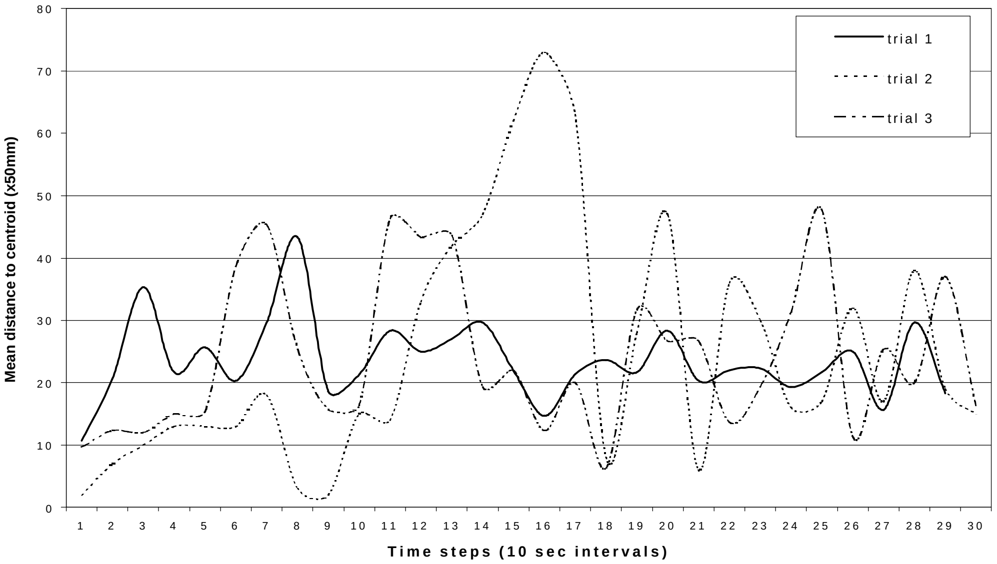

Figure 11: 3 Trials of homing on a beacon and robots showing mean distance to centroid of robots.

When a robot moves beyond the range of the beacon or another robot it will stop and slowly drift turning gently with the air currents. This random movement helps the robot to re-acquire the beacon or the transmission of another robot, at which point it will re-converge on the beacon or clump with the other robot.

5. Discussion

The severe payload constraints placed on the robot design allow only very limited power to be carried. Therefore, the power available for propulsion is minimal. This restriction on power allows for only very small forces to be generated by the motors and this coupled with the constant perturbations of the environment (air currents) lead to very imprecise control. The limitations of the system make it ideally suited to the use of collective minimalist strategies [Melhuish, 1999], where agents have only very limited power, sensing and computation. Instead of trying to engineer out the imprecision with a complex control scheme, we exploit the inherent randomness of the system. It was found that a 360-degree IR transmitter was not needed when a 180-degree transmitter that is constantly moving could have the same net effect.

By employing these methods in the design of our control system it has been possible to get a group of flying robots to home in on a static beacon, and to form dynamically stable groups in the presence of frequent perturbations.

The scalability of the system is limited in a number of ways:

- There are a finite number of available channels useable by the infrared localisation system before noise and interference become a problem.
- The physical size of the arena only allows for a small number of robots before it becomes overcrowded.

It is expected that as the number of robots increases they will be pushed outwards away from the beacon increasing the mean distance. As more robots are added the beacon signal will become obscured by the robots making it more difficult for them to home in thus lowering the performance of the system. This occlusion problem could be solved by using a technique referred to as ‘secondary swarming’ [Melhuish, 1999] where robots who can detect the beacon transmit their own signal and become a secondary source for other robots to home in on.

6. Acknowledgements

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