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Convoying: using chorusing to form travelling groups of minimal agents

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Abstract

We have previously used a biologically-inspired chorusing mechanism to control group size in an environment containing many simulated minimal agents. We now modify the technique to produce travelling groups of a particular size (convoys). An agent in a group of the desired size enters a primed state, emits a signal after a delay, and at the end of the signal moves off to the next destination; other agents in the neighbourhood which are in the primed state and detect the signal also move off at the same time, forming a group. Several such travelling groups in succession can be produced. © 1999 Published by Elsevier Science B.V. All rights reserved.

Keywords: Minimal agents; Biological inspiration; Travelling groups; Chorusing mechanism

1. Introduction

This paper is the most recent in a series dealing with the generation of useful behaviour from minimal mobile agents using biological strategies. The use of minimal agents is intended to shed light on the use and usefulness of robots with severely constrained sensory, motor, computational, and communication abilities, such as micro- or nano-robots. Biological strategies adapted from bacteria and insects, especially social insects, have been found to be suitable for deployment on simple agents. Previous work covered the use of minimal sensing and locomotion to approach a source of stimulation in a noisy environment [7], minimal communication to improve swarm integrity when following a moving source [8], and synchronised chorusing to control swarm size [9,10]. This paper reviews the operation of the chorusing mechanism for the control of group size, and shows how it can be extended to produce from a large number of minimal agents a succession of small groups which each move away as a group from the site of their formation.

The control of group size in collective robotics has received relatively little attention. It may be required for a number of reasons. For example, if a localised resource is sufficient for only a limited number of agents, there is little point in attracting extra agents to the resource. Again, it has been established by at least two sets of robot experiments [2,5] that there may be an optimum number of robots for carrying out a given task under certain circumstances; in such cases, the control of the size of the group undertaking the task may be critical to achieving the task quickly or efficiently. Producing and maintaining travelling groups (convoys) of a particular size is a behaviour which would be useful in a situation where a task requiring a certain number of agents had to be carried out many times in succession – for example, when a number of heavy items requiring several agents to move them had to be transported between two locations.

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The emphasis in this work is on techniques which can be used on homogeneous robots; among other factors, homogeneous robot systems are potentially more robust with respect to individual robot failure than non-homogeneous systems. This bias excludes any possibility of using robots with previously designated unique behaviours (e.g. dedicated 'leader' robots) and to some extent even discourages the use of robots which are temporarily allocated some unique role. A basic idea underlying the control of group size in a homogeneous system is that each agent should individually derive an estimate for the size of any group of which it is effectively a member, and should then (a) approach the centre or focus of the group if the estimated group size is less than or equal to some internal parameter expressing the 'desired' group size, or (b) move away from the centre or focus if the estimated group size is too large. If the group is required to form at a particular point, then we assume that there is something at that point which can be sensed by the agents, and used as a focus for the clustering process; we call this aggregation at such a point 'seeded clustering'. It is convenient to begin with the situation where the point is occupied by a source, or beacon, which produces some omnidirectional field with a strength which reduces with distance from the source. Motion towards or away from the group can therefore be arranged by moving towards or away from the beacon.

It will be convenient to use the same setup used in the previous work [9,10] on these simulated minimal agents. They exist in a circular arena, of radius 600 units, at the centre of which is a beacon producing energy with an intensity which falls off with the square of the distance from the beacon, and which becomes undetectable at a distance of 600 units. The arena may also be pervaded by background energy of the same type, which fluctuates randomly (with a Gaussian distribution) at each location about a mean value which is a function of the maximum beacon intensity. Where such noise is present, it has the effect of progressively increasing the signal to noise ratio with distance from the beacon. Examining the trajectories produced by a given algorithm in various regions of the arena allows one to see the influence of the changing signal to noise ratio, which is extremely useful in the development phase. The agents have an axis of symmetry (front-rear) and can detect the energy from the beacon with their two 'eyes', which have a restricted acceptance

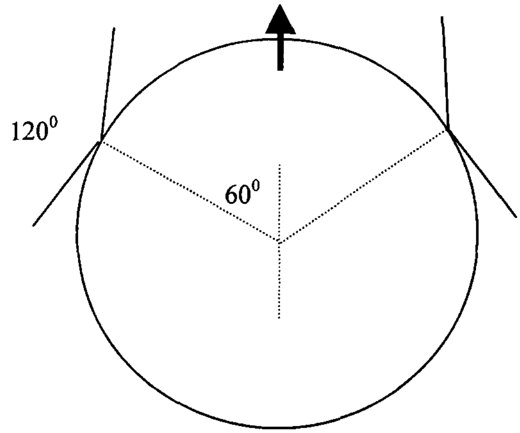

Fig. 1. Arrangement of 'eyes' on minimal agent.

angle (120°), and are fixed on the left and right of the axis of symmetry at an angle of eccentricity (60°) to the axis (Fig. 1).

Agents move at each discrete time step by rotating through an angle, and moving forward by a certain amount (the step length); both factors may contain a random element. Algorithms controlling movement are of the form:

if (condition on sign of difference between L and R sensor) *then*
  rotate (some angle) and
  move forward (some step length)
else
  rotate (some other angle) and
  move forward (some other step length)

Such algorithms can produce net motion towards, or away from, beacons or other sources of excitation. The trajectories are determined by factors such as algorithm type, algorithm parameters, environmental noise level, acceptance angle, and angle of eccentricity; their forms may range from apparent random walks to zig-zags, spirals, and regular or irregular orbits round the beacon [7].

A very simple method of achieving seeded clustering with control of group size is to arrange for the agents to reduce the intensity of the attractive signal by the merely passive fact of their presence. This was used in an early study of aggregation [11]; robots were attracted to a lighted box in an arena, but robots reaching the box blocked the light from the view of the other robots, resulting in no more robots being attracted to the box once there were enough to completely block the light. This use of passive properties is an attractive and neat solution, but works only when the number of agents required to block the light just happens to be the required group size; it is difficult to tune, and is a rather precise function of the nature of the environment, task, and agents, so it cannot be extended to serve as a general method. Active properties offer more potential generality, and we have adopted the following set of minimal capabilities: the agents will be able to transmit and receive some actively broadcast signal, omnidirectionally transmitted and detected, and decreasing in intensity with some function of distance; and each agent will be assumed to contain some internal parameter related to the size of group required.

Some strategies satisfying this restriction can be ruled out after some quite general considerations. One factor of interest is the power of the signal. (For an insightful study of many aspects of signalling in animals, including power, see [3]). Since the method of regulation is constrained to be active, each broadcast by an agent will use power, so in the interests of economy some means of reducing the power would be useful. Further, the range will be a function of the broadcast power; a long range would require a high power handling capacity, which is likely to use more structural resources than a lower power arrangement. An intermittent broadcast at high power will achieve range, at the cost of losing temporal granularity; this intermittent high power need not require the capacity for high power generation, as some accumulator mechanism can be used to store energy which is suddenly released to give a high instantaneous power, just as the flea winds its legs up over a period of time and releases them to make a leap. We therefore decided to explore the use of an intermittent signal, and ruled out looking at the summation of constantly transmitted signals, for example from agents within a certain distance of the source.

The simplest intermittent signal is a series of brief pulses, each of which is the equivalent of a click. It is characteristic of a click that two clicks will rarely overlap. If we assume that the intensity of a click must exceed some threshold in order to be registered by an agent, this means that the range over which a click can be detected will be fixed at some maximum. In contrast, a longer signal which overlaps other such signals can be expected to summate, and so will typically be detectable at a greater distance than a single signal, other things being equal. Although it would have been quite simple to devise a clicking mechanism – for example, clicking when close to the source, leakily integrating the time series of clicks, and moving away from the source if the integrated quantity was higher than the group size threshold – this would have a fixed maximum range of action from the source. It is desirable that the signal that the group is already large enough (or too large) should be detectable at the largest possible range, and so it was decided to investigate signals which were brief (saving power) but which could gain in range by being superimposed. This train of thought led us to study reports of natural systems which used such brief repeated signals. There are many such systems in nature; the best known are probably the sound choruses of crickets and frogs, and the light flashes of fireflies.

There is a large and fascinating literature on chorusing in crickets, fireflies, and frogs; particularly useful and accessible texts are [4,6,12]. An outstanding characteristic is that most of the creatures which chorus, or broadcast intermittent signals in synchrony, appear to use a similar mechanism for synchronisation. Greenfield [6] calls this mechanism 'the basic phase delay interactive algorithm'; essentially, a sawtooth pacemaker which produces a chirp when it rises to its maximum level is reset to the basal level by the perception of a chirp from another animal. If both animals have the same pacemaker period, they will be in synchrony on the subsequent chirp of the animal which interrupted. There are of course many variations on this theme, including alternating rather than synchronous chirping, but most chorusing appears to follow this rule. The function of chorusing can be very varied, and is not always obvious. One clear function is that of increasing the range of a group signal while retaining the temporal features which enable it to be identified and discriminated from other signals using the same modality. The role of the signal itself may be to attract females for mating, or to confuse predators by making signal localisation difficult. However, we have found no mention of chorusing being used to regulate group size.

We have implemented chorusing as follows. The agents are able to produce and detect energy in a modality which we characterise as sound, which is broadcast as a 'chirp' of a given duration (6 time steps) with equal strength in all directions, and detected by a single 'ear' which is uniformly sensitive in all directions. The intensity of the signal obeys an inverse square law, and there is a fixed threshold for the detection of any chirp energy. After emitting a chirp, an agent goes into a refractory period (20 time steps) during which it is unable to chirp again. At the end of the refractory period, it enters a 'listening' period (up to 20 time steps) during which it may initiate a chirp at any time with some constant probability, or when it hears any other agent chirping; if it has heard no chirp by the end of the period, it will chirp then. When several agents are within range of one another, this simple arrangement produces synchronised choruses. This is slightly different from the basic phase delay interactive algorithm; it is in fact a phase advance interactive mechanism. We made this change because this application requires rapid synchronisation, and the delay mechanism prevents the appearance of the synchronised signal for a whole cycle. No adverse effects of the change have been noted.

The agent can exhibit two related types of movement in relation to the beacon, each expressed in simple rules. Both depend on comparing the sensed beacon intensities in the left (L) and right (R) eyes. In the first, the attractive behaviour, the rule is:

if (L > R) *then*
 rotate left 60° and move 4 units
else
 rotate right 60° and move 4 units

This deliberately crude and noisy taxis rapidly brings an agent close to the beacon and keeps it there. In the second, repulsive behaviour, the rule is:

if (L > R) *then*
 rotate right 60° and move 4 units
else
 rotate left 60° and move 4 units

This will rapidly move an agent away from the beacon towards the periphery.

At any time, the rule to use is determined by comparing a variable derived from the estimated group size with an internal parameter related to the required group size.

There are a number of possible characteristics of the choruses which are a function of group size; all depend on the probabilistic initiation of a chirp during the 'listening' period. For example, the mean interval between choruses is a decreasing function of the number of agents contributing to the chorus. However, for an agent to sense this, it requires the accumulation of a number of time measurements. Rather than using time measurements, we reasoned that the detection of simple classes of events would be more minimal. A simple event classification is whether the agent initiated the current chirp itself, or whether it responded to a chirp from another agent. In a group of n chorusing agents, an individual agent will produce one unstimulated chirp in every n chirps on average. By forming a recency-weighted estimate of the ratio of unstimulated to stimulated chirps, and comparing this to the ratio expected for the required group size, we found we were able to produce regulated group sizes. However, a more economical statistic turned out to be the number of stimulated chirps between successive unstimulated chirps; the expected value is $(n-1)$ one less than the group size. We can therefore form an initial estimate γ_e of group size from the number of stimulated chirps c, taking the form: $\gamma_e = (c+1)$. Because this proves to be a very noisy estimate, we use instead a time-weighted average of successive values of γ, of the form

$$\gamma_t = \alpha\gamma_e + (1-\alpha)\gamma_{t-1}$$

where γ_t is the time-weighted estimate at time t, γ_e is the raw estimate $(c+1)$, γ_{t-1} is the time weighted estimate from $(t-1)$, and α is the weighting factor ($\alpha = 0.85$ in all experiments reported here). The internal parameter associated with a given desired group size was initially calculated in the same way from the expected value of γ_e.

This arrangement performed reasonably well, except that the actual group sizes formed tended to be rather lower than the nominal required group sizes, especially in the presence of noise [10]. This is not a serious problem: from the practical point of view, all that is necessary is to adjust the internal parameter value using empirical data; from the theoretical point of view, the use of the expected value of γ_e takes no account of the noise inherent in the situation, and so perfect performance would not be expected. In addition, the algorithm tended to become ineffective for large desired group sizes, which would clearly pose a serious problem if the intention was to deal with such

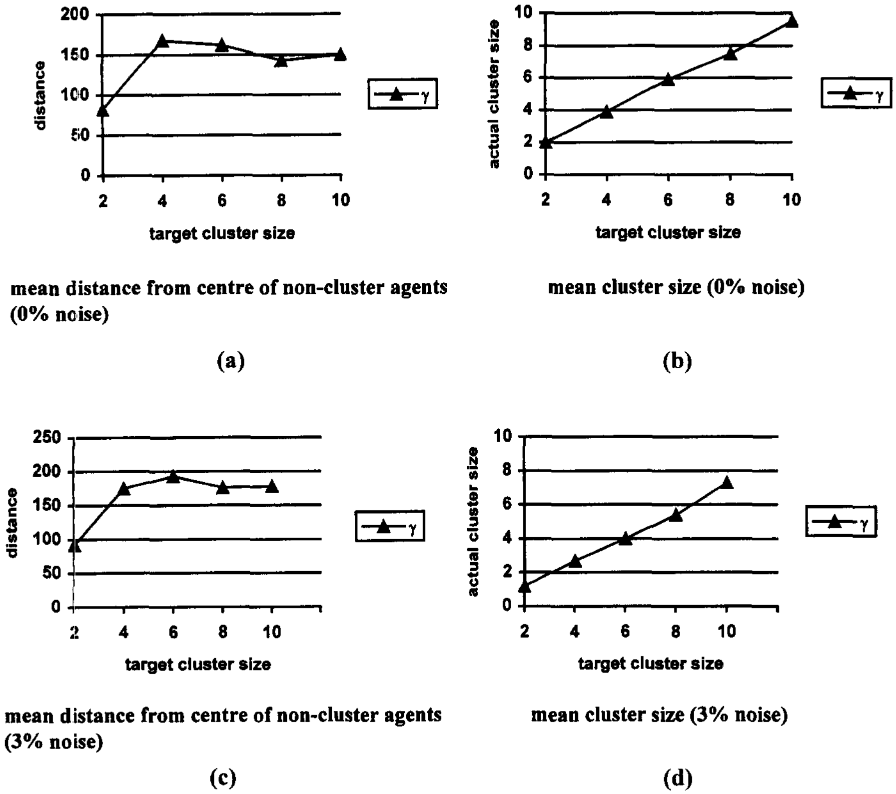

Fig. 2. Performance of improved algorithm for the regulation of group size under two conditions of noise.

large groups. The agents excluded from the group were of course still attracted to the beacon, and so the idealised arrangement should consist of a compact group at the beacon, and a surrounding annulus of excluded agents. Although measurements of the mean distance of group agents and non-group agents from the beacon revealed that group agents were on average much closer to the beacon, a clear separation was not always apparent visually, and there was frequent interchange between the two populations.

Two changes were introduced to give more stability, by reducing noise, and also by reducing the effects of noise. The first is known in the study of this class of movement algorithms as orthokinesis, and is often found in nature [13]; it is the reduction of the agent's speed (here represented as step length) as a function of its closeness to the beacon. This reduces the mobility of those agents close to the beacon in comparison with those further away. The effect on the regulation of group size under noisy conditions is to improve the control of large group sizes, which otherwise tend to fall well below the nominal requirement. The second change involves the introduction of a 'silent period': an agent sensing that it is in a group which is larger than the required size refrains from broadcasting its chirp for a fixed period, during which it is moving away from the group. The effect of this was mainly to increase the average spatial separation between group and non-group agents, and so to reduce the interchange between the two categories. Fig. 2 shows the performance of the final algorithm in terms of final group size and mean distance of non-group agents under two conditions of noise, 0% and 3%.

2. Forming travelling groups

To force a chorusing group of the right size to leave the beacon together and head for some other destination, two requirements must be met:

(i) the members of the group must leave the beacon at approximately the same time,
(ii) the members of the group must stay together while travelling to the other destination.

Our initial thoughts were that the intrinsic characteristics of the chorusing mechanism would go a long way towards producing (i), and the success of (i) can also provide much of what is required by (ii) without introducing special measures for controlling a travelling group. Chorusing usually involves the group members chirping within one time step of one another, and so, in a stable group, they will form their estimates of group size almost at the same time. If these estimates are accurate, then all group members will leave the beacon at almost the same time, achieving requirement (i). If this happens, each agent will then head towards the new destination (which may be conveniently represented by a new beacon, to which agents become exclusively sensitive on leaving the original beacon). If the trajectory defined by their locomotion rule is approximately a straight line, all the agents will move directly towards the new beacon at the same average speed. This will give the appearance of moving as a coherent swarm; in fact, this is only an appearance, as the agents do not interact with one another to maintain the integrity of the 'swarm', and errors or disruptions will be cumulative, leading to the eventual disappearance of swarm-like characteristics if the beacon is sufficiently distant, and noise and disruptive interference is strong enough. We prefer to call such an aggregation a pseudoswarm [8]. In the spirit of minimalism, we decided to employ only pseudoswarming in this investigation.

3. First results: serial streaming

First simulations showed that clearly discriminable travelling groups of agents were not often formed by the operation of this simple extension to the chorusing mechanism. The general picture is that individual agents leave the group at frequent but irregular intervals and travel towards the second beacon, forming a noisy serial stream, but no coherent spatio-temporal grouping was apparent either from the time series of successive departures, or from simply watching the simulated activity (Fig. 3). This was the case even when sensor noise was turned off. This appears to be a consequence of the fact that the agents' estimates of the size of any group they are in are very noisy and irregular when the group is first formed; this is because there are many agents present on the borderline of chirp audibility, whose movements can add unsynchronised chirps, or remove chirps. The net effect of this is that estimates of group size may not be well synchronised, and the first agent to estimate that it is in a group of the target size will leave the group, immediately reducing the group size and preventing others from leaving until the group size is increased by the arrival of one or more additional members.

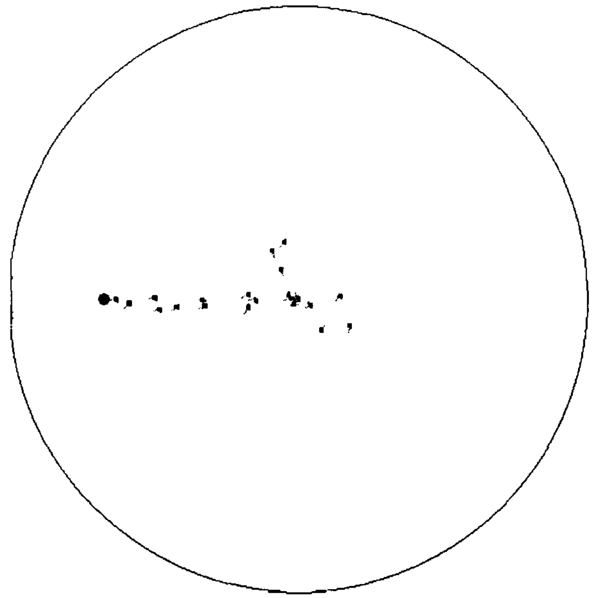

Fig. 3. Serial streaming from the beacon at the centre (unmarked) to another beacon on the left.

4. Improving performance

We therefore decided to investigate simple ways of stabilising the situation so that travelling groups of the correct size could be formed reliably. We had noticed in previous work that a chorusing group at a beacon site appeared more stable after some time than when it had first formed. This appeared to be at least partly due to the ability of a group, once formed, to repel supernumerary agents away from the beacon to a distance at which it became unlikely that an agent could move close enough to the group to disrupt it. Very

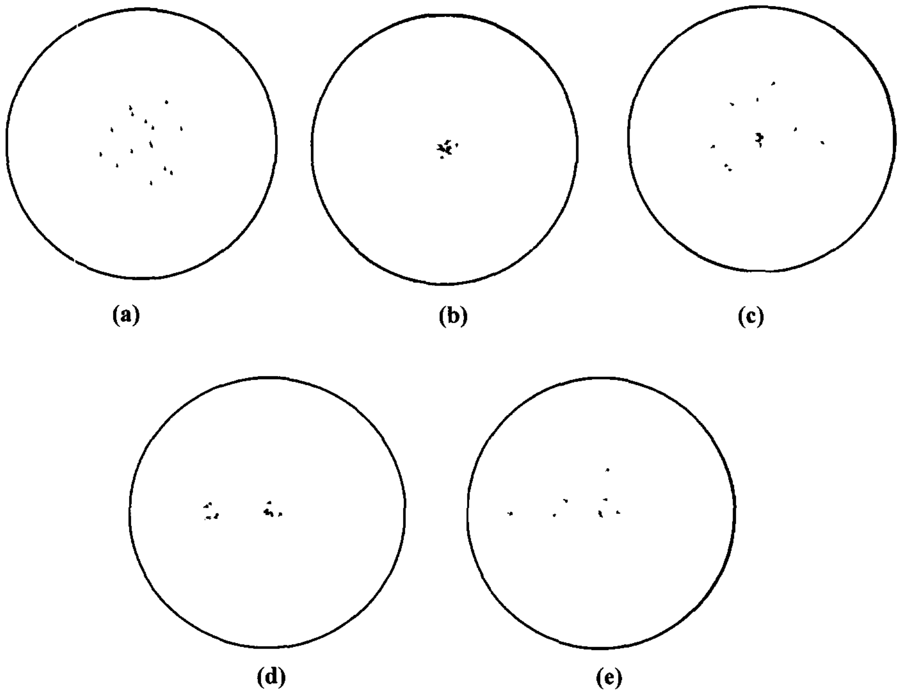

Fig. 4. Typical screenshots showing the key stages of convoying (see text for descriptions).

often, the effect produced would be of a tight cluster around the beacon, surrounded by a clear region, and then by an annulus containing the remaining agents. Fig. 4 shows this effect: Fig. 4(a) shows the start, with agents randomly distributed over the arena; Fig. 4(b) shows the agents all approaching the beacon; Fig. 4(c) shows the stable group around the beacon and the annulus of repelled agents. We therefore reasoned that a mechanism which delayed the departure of the group for some time after its initial coming together might allow the formation of this more stable spatial structure, and would allow time for the individual estimates of group size to become more accurate, or at least consistent.

However, introducing a delay also introduces the problem of ensuring that group members depart at the same time, because we cannot assume that the agents possess very accurate timing methods. A 'trigger' to synchronise departure seems to be necessary, and this implies some form of signalling between the group members. In order to keep things as simple as possible in the spirit of minimalism, this should not involve any additional signalling channels, and so some adaptation of the chirp mechanism was indicated. Our solution was the following: when an agent first estimates that it is in a group of the correct size, it enters what we call the primed state and starts an internal timer, counting down. No other aspect of its behaviour is changed-it continues listening, chirping, and moving as before. The first agent to time out produces an extended chirp, and at the end of the chirp leaves for the new destination; any other agent in the primed state hearing an extended chirp also departs at the end of the chirp. The expectation was that, by the time the first extended chirp was produced, a coherent group of the target size and consisting entirely of primed agents would have been formed around the beacon, with all supernumerary agents in the distant annulus. The members of the primed group would then move off simultaneously.

5. Results of improved algorithm

Fig. 5 shows the results of employing this strategy with a very long countdown-more than 35 000 time steps. Consistently sized (the small error bars are

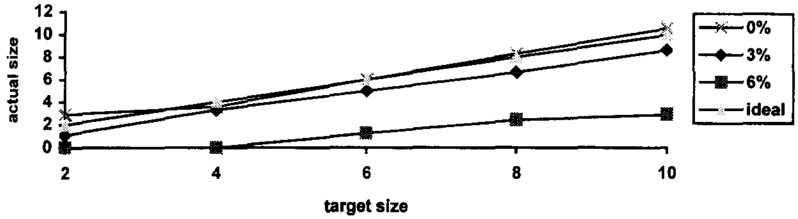

Fig. 5. Relationship between target group size and actual group size for three noise levels.

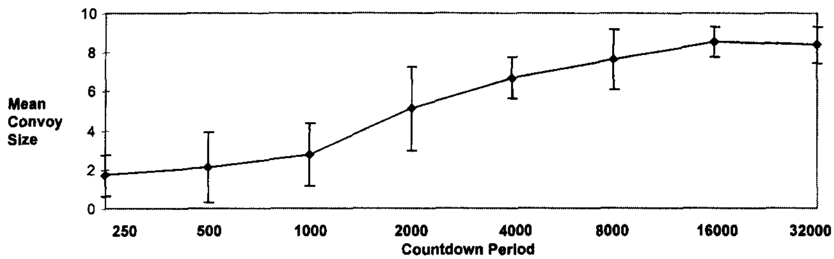

Fig. 6. Effects of countdown period on convoy size.

not shown) and apparently coherent groups of agents leave the main swarm at fairly regular intervals, and travel to the second beacon. The addition of sensor noise reduces the group size in comparison to the nominal target size, as found in previous work. Fig. 4 shows a typical set of screen shots: after the central group and surrounding annulus have emerged in Fig. 4(c), the central group leaves and travels towards the second beacon, and at the same time the annulus collapses towards the central beacon Figs. 4(d); in (e), a central group and annulus has again formed, and subsequent progress alternates between the situations in Figs. 4(d) and (e) until insufficient agents are left to form another group.

The use of a long countdown imposes a hard limit on the rate at which convoys can be generated. We therefore carried out further simulations to establish the effects of using shorter countdowns. Fig. 6 shows the effects of different countdown periods on both the mean and standard deviation of group size. The nominal 'desired' group size is eight; as expected, as countdown periods become short, convoy sizes become more irregular and inaccurate. We can therefore conclude that this general method can be used to generate convoys even at relatively short time intervals, but at the cost of increasing variability in group size.

6. Conclusions and further work

The biologically inspired strategy of chorusing, previously used to control group size in simulated minimal agents, has been shown capable of being augmented to provide an effective means both of forming groups of a particular size at a location, and of despatching them as a group to another nearby location. The accuracy and variability of the group size produced is adversely affected by an increased rate of despatching the groups. However, while these simulations can serve as a useful guide to what may or may not be possible, they by no means guarantee that a usable system could be constructed along these lines. We are therefore modifying our fleet of 15 experimental robots (known as U-bots) to examine the performance of these algorithms in the real world. Although these robots are of a size that imposes no practical restrictions on sensing, locomotion, or computation, we can be reasonably confident that running these robots with the restrictions used in the simulations will give us a good indication of the potential for using these techniques in the micro- and nanoworlds where such restrictions will be inevitable. Fig. 7 shows a U-bot carrying the prototype chirping system.

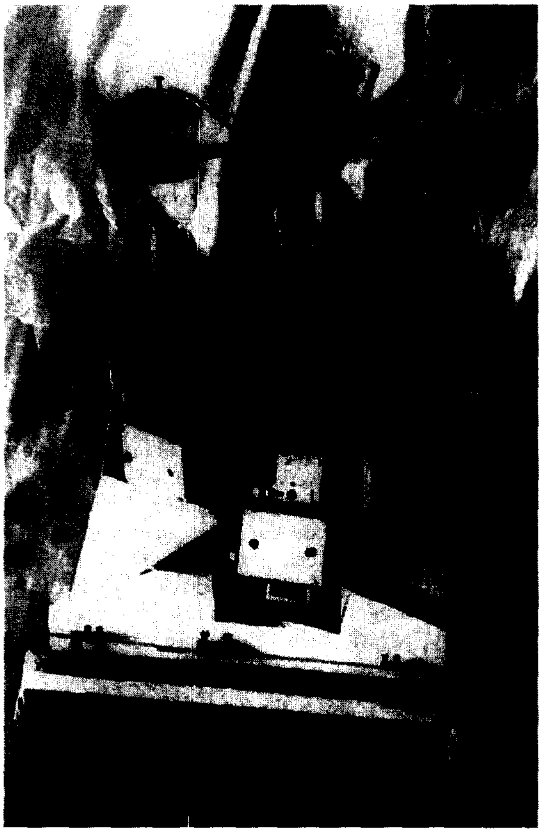

Fig. 7. A U-bot with omnidirectional ultrasonic transmitter and receivers.

The U-bots were designed and built in our laboratory to provide a flexible and capable platform for a range of collective robot experiments. They have the following features:
- size: the robots are small enough (23 cm diameter) to be easily portable, yet are large enough to operate on most floor surfaces, and to carry most sensor types (ultrasonic, IR, CCD video cameras),
- manoeuvrability: differential drive, powerful motors, and high-resolution optical quadrature encoders enable turning on the spot, reversing, and tight control of speed and position,
- endurance: each robot will run for around 3 h under conditions of frequent acceleration and deceleration, with all electronics operational,
- computational power: a Motorola 68332 processor with up to 16 Mb of memory provides ample capacity,
- flexibility: extra power rails, multiplexed I/O ports, and A/D conversion provide for the addition of a range of sensors and effectors at a later date,
- reliability: the precision machined aluminium chassis bears all structural loads, and provides a secure fixing for PCBs, sensors, and effectors; the gearboxes are protected from shock loads by a preset torque-limiting clutch; all input, output, and power lines are protected or fused.

The inverted cone in the centre is an omnidirectional ultrasonic transmitter; the receivers are inside the two inverted cones on the left and right. A pair of infra red detectors correspond to the eyes; the beacon is a static omnidirectional infra red transmitter. Initial trials with the system have shown that the infra-red system has an effective maximum range of over six metres, and the ultrasonic system has a range of over three metres; both show good inverse square law characteristics and adequate resolution. Our arena is 10 m in diameter, and so we are in a position to reflect the characteristics of our simulations quite closely.

Acknowledgements

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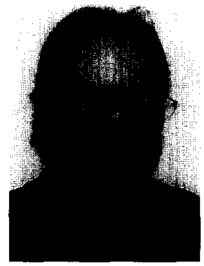

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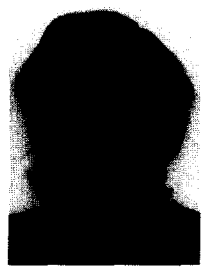

Owen E. Holland received a B.Sc. in psychology from Nottingham University in 1969. After working in the electronics industry for many years, he developed research interests in artificial life and, especially, in emergent collective behaviour. He is currently a senior research fellow in intelligent autonomous systems at the University of the West of England, Bristol, UK.