Proceedings of AUVS-92, Huntsville AL, 22-24 June 1992.
Reprinted in **Unmanned Systems**, Fall 1992, volume 10, nbr 4, pp 28-34.

COMMAND CONTROL FOR MANY-ROBOT SYSTEMS

Douglas W. Gage

NRaD Code 531
Research Development Test and Evaluation Division
Naval Command Control and Ocean Surveillance Center
San Diego, CA 92152-5000

ABSTRACT

Rapidly evolving sensor, effector and processing technologies, including micromechanical fabrication techniques, will soon make possible the development of very inexpensive autonomous mobile devices with adequate processing but fairly limited sensor capabilities. One goal which has been proposed is to employ large numbers (more than 100) of these simple robots to achieve real-world military mission goals in the ground, air, and underwater environments, using sensor-based reactive planners to realize desired emergent collective group behaviors. One key prerequisite to realizing this goal is the capability to command and control the system of robots in terms of meaningful mission-oriented system-level parameters. A commander requires an understanding of a system's capabilities, doctrine for employing it, and measures of effectiveness to assess its performance once deployed. It is thus necessary to relate system (ensemble) functionality and performance to the behaviors realized by the individual autonomous elements.

This paper describes a program of analysis, modeling, algorithm development, and simulation which has been undertaken to develop, refine, and validate this basic approach to real-world problem solving. The initial thrust has been to develop generic behaviors, such as blanket, barrier, and sweep coverage, and various deployment and recovery modes, which can address a broad spectrum of generic applications such as mine deployment, minesweeping, surveillance, sentry duty, maintenance inspection, ship hull cleaning, and communications relaying. Initial simulation results are presented.

1.0 INTRODUCTION

The critical sensor, effector, and processing technologies that are prerequisite to the development of the military mobile robots of the 21st century are evolving rapidly. Moreover, while major thrusts in the development of military mobile robots have been undertaken in the areas of Unmanned Ground Vehicles (UGVs), Unmanned Air Vehicles (UAVs), and Unmanned Underwater Vehicles (UUVs), continuing developments in solid-state sensor and effector technologies suggest that unexploited opportunities exist at the "lower end" of the spectrum of robotic vehicle functionality and performance [1, 2]. In fact, the emerging field of "micromachines" (also termed "microdynamics", "mechatronics", or "microelectromechanical systems") was selected

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1992**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Command Control for Many-Robot Systems**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Navy Command, Control and Ocean Surveillance Center Division 531 RDT&E San Diego, CA 92152-7383**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**14**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

by the New York Times in its 1991 New Year's Day Science Section as one of the "10 Critical Technologies" for the 90s [3].

The goal of this work is to achieve a variety of military mission goals through the collective behavior of large numbers of relatively simple, inexpensive, interchangeable, autonomous elements, rather than through the explicitly purposeful, complex, perception-based behavior of a single very expensive, highly sophisticated (and currently technically or economically infeasible) unit. The approach is to design and implement vehicle behaviors that both (a) can support real-world missions and (b) are realizable with current levels of sensor and processing technology, even in the object- and obstacle- rich environment of ground-based applications, where useful missions generally require high-bandwidth visual-perception-based vehicle navigation, guidance and control beyond the capabilities of current sensor and processing tools.

The use of large numbers of small and inexpensive vehicles can be applied to a number of situations of military interest: minesweeping, mine deployment [4], surveillance, sentry duty, communications relaying [5], various types of search, maintenance inspection, carrier deck foreign object debris (FOD) disposal, and ship hull cleaning come to mind.

Note that it is possible to characterize the navigational behavior needed to realize each of these diverse applications as "maintenance of an appropriate spacing relationship between the participating elements, either in static deployment or in group motion". This concept of coordinated positioning and movement in concert is the focus of this work.

While a central coordinating controller could be employed to calculate a desired position or trajectory for each element in a group, which could then be downloaded and executed, this is at best an inefficient and at worst a nonviable approach to the problem. Execution of the plan could be hindered by unpredictable events (e.g., excessive current, unknown obstacles, enemy actions). The central controller would need to receive perhaps quite specific information from the affected elements in order to modify the plans to take the contingency into account, and this information might not even be available to the elements themselves. Time and/or processing and/or communications resources may not be available to support either (a) the communication of the required data to the central controller, (b) the processing to produce the modified plan, or (c) the communication of the plans back to the executing elements.

The solution is to do with robots what is actually done today with humans in such applications: "You guys line up at arm's length distance, and then all walk along together, picking up whatever you find as you go". The motion of each element is based on the motions of the other elements, more strongly on the motions of the nearest neighbors, but with some reference to the more remote elements as well. Thus, navigational coordination is achieved by using sensor inputs (each element sensing the position of its neighbors, relative to itself), vice explicit communications channels. Active sensors might be modulated to facilitate the control process (by, for example, emitting acoustic "peeps" at a rate inversely proportional to peak emitted power). The world model of each of these robots will be strongly "self centered", and populated with its fellows.

Animals, of course, use similar modes of control when moving as flocks, herds, and schools. While the literature on animal herding, flocking, and schooling is mostly descriptive or coarsely analytic [e.g., 6,7], a synthetic approach to the study of such group behavior has been pursued by Craig Reynolds [8] in developing an animation sequence of a flock of birds. He had found that he was unable to produce a realistic flock by drawing it a bird at a time; instead he implemented a flock of simulated "birdoids" which attempted to maintain a desired spacing relationship with their neighbors.

While ethology (the study of animal behaviors) provides a natural language to discuss systems which display group behavior, and the focus on emergent group behavior fits under the broad umbrella of the emerging field of "Artificial Life" [9], it should be stressed that this kind of work fits into the mainstream of the discipline of intelligent control.

2.0 SYSTEM CONCEPT

The defining feature of the systems considered in this paper is that the number of mobile robotic elements is large enough so that the system command control interface must “hide” the individual elements from the commander of the system. The elements don’t have to be small or inexpensive, but economic and technical factors make it highly likely that they will be.

A system, then, consists of a large number of identical (see the discussion of caste and role in sections 2.3 and 4.0) elements, each possessing: (a) some measure of mobility -- this may be fairly limited, so that, for example, in an underwater application the elements may be capable of regulating only their depth in the water column, drifting with the currents; (b) some sensor capability that allows each element to measure, at least crudely, its position with respect to at least its nearest neighboring elements; (c) some mission-capable sensor or effector, which may be the same as the sensor capability listed above; (d) optionally, some communications capability, which may make use of the sensor capability; and (e) some processing capability, which implements algorithms that use the mobility effectors to maintain a specified positional relationship to its neighbors, as measured by its sensors, so that the mission-capable sensors or effectors collectively accomplish the desired mission objectives.

2.1 Ensemble Motion Behaviors

The key to achieving mission objectives, then, is to ensure that the aggregation of the simple mobility behaviors exhibited by the individual elements of the system results in the desired behavior of the group as a whole. The level of abstraction is such that collisions between elements or of individual elements with discrete obstacles are not dealt with: the elements may be considered to be small enough that collisions between them are very unlikely, robust enough that collisions don't damage them, or expendible enough that damage to or loss of elements doesn't matter at the system/mission level.

Coverage Behaviors: In many cases, the desired group behavior is the maintenance of a spatial relationship which adapts to specific local conditions to optimize the performance of some function, often characterizable as "coverage". In these cases it is necessary to develop precise measures of effectiveness which meaningfully characterize the overall system performance in the context of specific mission goals. For example, a surveillance group should be large and sparse if the goal is to maximize the number of enemy detected per unit time over a wide area, but small and dense to minimize the probability of leaving any enemy undetected within a smaller swept area. Three varieties of coverage behaviors, graphically depicted in Figure 1, can be distinguished:

Blanket coverage: The objective is to achieve a static arrangement of elements that maximizes the detection rate of targets appearing within the coverage area.

Barrier coverage: the objective is to achieve a static arrangement of elements that minimizes the probability of undetected enemy penetration through the barrier.

Sweep coverage: the objective is to move a group of elements across a coverage area in a manner which addresses a specified balance between maximizing the number of detections per time and minimizing the number of missed detections per area. (A sweep is roughly equivalent to a moving barrier.)

Here is a table of potential applications of the three types of coverage behaviors -- it is sometimes possible to think of different types of systems to address the same requirement:

APPLICATION	COVERAGE TYPE
Mine deployment	Barrier
Mine sweeping	Sweep
Reconaissance	Sweep
Sentry duty	Barrier
Communications relay	Blanket
Maintenance inspection	Sweep
Carrier deck FOD disposal	Sweep
Ship Hull cleaning	Blanket or Sweep

Formation Behaviors: These represent an alternative to coverage behaviors, in that the desired group behavior is the maintenance of an explicitly specified spacing relationship between elements. For example, if a group of USVs (Unmanned Surface Vehicles) or low-flying UAVs are to serve as a decoy battle group, then the spatial relationship between the elements must reflect that seen in a real battle group. The apotheosis of this class of behaviors is the drill team or marching band, whose elements are synchronized to each other spatially, and synchronized in time to the accompanying music. It may sound frivolous, but it is not an easy problem! Perhaps the simplest example of a formation behavior is the one-dimensional case of convoying ground vehicles along a road; a sensor based approach to maintaining the spacing between vehicles traveling in a convoy was described in [10].

In addition to coverage and formation behaviors, which represent "steady state" and "bulk" behaviors of the system, it is necessary to consider and provide for the various relevant spatial and temporal “boundary condition” behaviors.

Deployment: the elements must be able to arrange themselves into an acceptable pattern starting from an initial arrangement that is easy to realize in a convenient deployment scheme. Possibilities include (a) at a single point (e.g., air drop in a canister, or off the back of a moving delivery vehicle), (b) in a linear pattern of appropriate density (e.g., sequential deployment from a moving platform), or (c) in a randomly distributed initial pattern, either dense or sparse (e.g., air burst dispersal).

Recovery: it must be possible (in at least some cases) to recover all (or the great majority of) the elements when the mission is completed, or (again, in some cases) even individual elements if/when they fail. The ideal mode of recovery would be to have the elements move autonomously to collection stations that "call them in". It should be possible to have multiple collection stations operating fairly close to each other at the same time. This collection mode must, of course, not provide a channel for enemy spoofing [11,12].

Navigation of the group as a whole: a mechanism is required to control the gross movement of the group as a whole, in order to put the group where it is needed to perform its mission. Examples of possible methods for achieving this control include: (a) biasing the motion of each individual element in the prefered direction (a real-time controllable "tropism" -- this will probably require that all elements share a common directional reference), and (b) using direct control of the motion of a small number of the elements, with the bulk of the group following due to the basic relative position control algorithm (like a sheepdog guiding a flock of sheep).

Many applications will require other generic behaviors, such as (a) calling for assistance when an individual element has failed, without interfering with the prosecution of the mission by the other elements, and (b) having elements bring themselves in for routine maintenance (battery recharging, for example) without disturbing the overall mission.

2.2 Analytic Considerations

Having defined a number of classes of desired mobility behaviors, the prospective developer of such a system must develop an adequate understanding of the complexities of behavior of systems consisting of large numbers of mobile elements. Here are some areas to consider:

Randomness of behavior: it may prove to be desirable to introduce elements of randomness into the navigational algorithms. In a real world system, this can help resolve potential deadlock situations, enhance mission sensor effectiveness, and counter possible enemy spoofing threats. In addition, in a simulated system, algorithmic randomness can be used to model some of the limitations of real world sensor and effector behaviors.

Obstacles and Traversability: the concept of traversability is important in two-dimensional (ground) environments: it may be necessary to identify the presence of point or extended obstacles, or, conversely, navigation may in fact be restricted to a small number of possible routes. Where this information has global (mission-level) significance, it must be made explicit and be communicated to the commander. At the navigation/mobility level, the system behavior must be robust in the presence of various types of obstacles: the whole herd should not tumble, one by one, off a cliff, nor should they pile up on top of each other at the end of a box canyon.

Internal Dynamical States: the gross motion of a flock can be described independent of the internal dynamics of the group which is realizing that gross behavior. Depending on the algorithms and the sensor capabilities, the same gross motion may be realized using a number of different strategies which result in quite different internal behaviors. A simplified taxonomy of these internal modes can be defined using the metaphors of physical states of matter:

If the elements of the flock maintain a rigid relative geometrical relationship as the flock moves, we can think of the flock as being a solid. If the geometric relationships are repetitive, the solid flock is crystalline; otherwise it is amorphous. If the elements move freely past each other, but the density of elements remains constant, then the flock might be considered to be a liquid. Finally, if the density varies, and individual elements can wander away, we might think of the group as a gas. Statistical measurements analogous to temperature and pressure may also prove useful in characterizing the group behavior.

2.3 Possible Biosystem Analogies

While it is certainly possible to make too much of the analogies between the artificial systems we are discussing and the behavioral mechanisms used by animals, it can be instructive to look to natural biosystems for possible approaches that can be adapted to our requirements. For example:

The flowing motion of an amoeba has the property that most of the elements on the outer perimeter of the flock are stationary at any given instant of time, as the group "flows through" itself in a toroidal pattern. In many situations, this would result in better sensor performance than if all elements were in constant motion.

Pheromones are chemicals that animals use to communicate. For example, ants leave a trail of pheromone to mark the trails between their nest and a food source. A simple artificial pheromone scheme like dropping tiny retroreflective glass beads could be of use in some applications. Key aspects of artificial pheromones will be the decay rate and the ease of detection by the enemy. Spoofing is also an issue -- an ideal pheromone would use an encrypted interrogation technique.

The human immune system and ant colonies [13] both provide models of how natural systems use a mix of elements of different characteristics and capabilities in order to achieve a desired goal. Some cells detect and "mark" invaders in the body, while other cells, seeing the marks, destroy the invaders. The caste system of ants divides labor similarly. What mix of capabilities makes sense to achieve a given mission most effectively and efficiently? In the world of security, the tasks of intruder detection, localization, identification, and neutralization require greatly different capabilities. It may make sense to employ large numbers of inexpensive sensors to perform the initial detection, then follow up with a much smaller number of much more capable units to assess the initial threat contact and to respond if the presence of an intruder is confirmed. Deneubourg [14] has demonstrated via simulation that sorting behaviors observed in ants can be produced by the simplest possible biasing of behavior by environmental cues.

Worker honey bees, which are capable of many different tasks, spend a significant portion of their time "patrolling" the hive, initiating their various productive activities in response to quite simple signals and cues. Honey bee colonies thus provide a model for achieving "purposeful" coordinated group action, responsive to changing environmental conditions, without employing a world model -- in fact, without explicit global decision making of any sort [15]. This property of quasi-intelligent "emergent behavior" resulting from the interaction of simple reactive plans is one which has been used in the context of simple vehicle systems [16], and which has been touted as the best basis for the development of quite complex systems [17]. The current approach is in this spirit.

3.0 SIMULATION PROGRAM AND INITIAL RESULTS

A program of analysis, modeling, algorithm development, and simulation has been initiated in FY92 with 6.1 funding, in order to validate the overall systems approach. The simulation initially models a 2-dimensional world, and each element knows the exact relative positions of each of its fellows; neighborhood models and sensor capabilities and limitations (radially symmetric at first) will be implemented in the second iteration of the simulation. Ultimately, the model will be further generalized by incorporating a third dimension and building more detailed models of sensors and sensor pre-processing.

The simulation program has been written on the Macintosh using Symantec's Think C compiler and associated development environment, while minimizing the use of Macintosh- specific constructs in order to maximize portability of the program to platforms with greater computational power. The program supports the creation of up to ten independently controllable behavior groups of elements (robots), with up to 200 elements total. The program user creates clusters of elements by specifying how many elements are to be created in each cluster, in what pattern (random distribution within a circle or rectangle of specified size and location), with what initial velocities (random distribution within a range of speed and course), and with what behavior (zero acceleration, specified speed and course, rendezvous at specified time and position, or one of several sensor-based flocking algorithms). The simulation navigates each individual element in terms of speed and course; realizing the requested speed and course in terms of throttle and steering is allocated to an unsimulated lower level controller, which also navigates around point obstacles, such as other elements. The behaviors of the different groups of elements can be changed by user command as the simulation progresses. A simulation run can be saved as a file containing a succession of kinematic frames, and replayed later.

Figure 2 presents a sequence of several frames from a simulation run, showing a group of 40 elements executing a “condensation” behavior, coming together from an initially dispersed configuration. The actual algorithm is very simple: if the minimum azimuthal angle subtended by all an element’s neighbors is less than 180 degrees (i.e., if it is possible to draw a line through the element so that all its neighbors fall on the same side of the line), then the element knows that it is “on the edge” of the group. Elements “on the edge” move at fixed speed down the bisector of the subtended angle; elements not “on the edge” remain stationary. Thus, the configuration “implodes”, with the “outer” elements “sweeping” the remaining nodes insward as the condensation continues. The angle-bisecting portion of this algorithm was first discovered by Sugihara and Suzuki [18], whose paper discusses a number of other interesting motion coordination algorithms. In a real application, a complementary (or in some implementations, “competing”) behavior would halt the condensation process as the desired element density is achieved.

The condensation algorithm and its simulation present some interesting features for discussion. First, the algorithm is highly robust, in the sense that, even if the sensor range is much smaller than the initial diameter of the configuration, the algorithm will produce a single compact group, as long as the sensor detections produce a connected graph. (If the graph consists of disjoint pieces, each piece will condense to form a separate group.) This is true because any element in motion is moving closer to the positions of all other elements that it can see. The second point is that the condensation process requires no global position information of any sort; the command to the group is not “condense to position LATLONG”, it is just “condense”. The third point is that the algorithm makes use of only azimuthal information from sensors, and has no requirement for range data. However, algorithms generally similar in effect can also be designed using range data only, or a mix of range and azimuth data, and this is an area of exploration for the continuing simulation effort. The fourth point is that, in its initial instantiation, with a discontinuity in element motion based on a binary decision of “on the edge” or “not on the edge”, the time-step simulation introduces an artifact of clustering at the “corners” of the configuration, as the different elements in a “corner cluster” play leapfrog, taking turns being “on the edge”. It is possible, however, that the concentration of forces introduced by this “artifact” might be considered a desirable feature in some combat situations, and the algorithm could be time-quantized to produce it with real (vice simulated) robots.

4.0 COMMAND CONTROL AND SYSTEM ISSUES

In order to make effective use of the resources at his disposal, a commander must understand the tools he has been given: he must know what he can tell each subordinate unit to do, what it is capable of doing, and what it is most likely to do when confronted by various contingent events. The parameters of the “game” the commander plays are established by doctrine and training. These same considerations apply to the use of an autonomous unmanned unit. The prospective commander must be provided with:

A model of unit functionality: an understanding of the range of missions he can assign to the unit -- essentially the semantics of the orders the unit can respond to.

A model of unit performance capabilities: an understanding of how far and fast the unit can move, the range and effect of its weapons and/or sensors, its capabilities for self-defense against various threats, the connectivity and effectiveness of its communications resources, and its requirements for logistical support.

A model of unit behaviors: an understanding of what the subordinate unit commander, based on his training and the specific orders he has received, will do in response to a wide variety of contingencies: how he will use his mobility, weapons, sensor, and communications capabilities.

The point of this work is to propose the concept of “coverage behaviors” as a generic paradigm for many-robot systems -- in other words, as a model of unit functionality -- relevant to a number of diverse applications. Ultimately, analytical tools for characterizing some aspects of unit performance capabilities will also be developed. This will involve modeling effector (sensor or weapon) effectiveness (probability of detection or probability of kill) as a function of the instantaneous geometry of the situation, and devising some reasonable way to integrate over time as an element approaches and then withdraws from a potential target. The key issue is properly representing the statistical independence of the probability of success over the relevant interval of time and distance. The plan, then, is to start with definitions of group behaviors and then develop measures of effectiveness (MOEs) for the sensors and effectors being supported by these group behaviors in order to validate the group behaviors in terms of the MOEs.

A model of unit behaviors must also be developed before real systems can be deployed -- this is in some sense equivalent to modeling the thinking of a “virtual subordinate commander”. If the unit behavior is to be truly adaptive, and not unacceptably “brittle”, it will be necessary to formulate explicit policies to deal with many contingencies that a human would deal with using “common sense”. It is not even easy to simply enumerate the possible relevant contingencies, which include numerous situations that would require no action other than sending a message to the commander in the form “something wierd is happening here...”.

There are other problems, too. For example, consider the deployment of a flock of 10,000 elements in a filled-circular pattern 1 km in diameter, centered on a target beacon. Suppose that one of the two 5,000 element canisters fails in deployment -- what do we want the remaining 5,000 elements to do? One obvious possibility would be to maintain the spacing of the elements, but reduce the diameter of coverage to about 700 meters. Another obvious possibilitiy is to maintain the 1 km diameter of coverage, but increase the spacing (from something like 8 or 9 meters apart on average, to about 12). Or we could split the difference. The point is that, while this call is a “high level” policy decision that might change from mission to mission, it has implications for the design of a “low level” condensation algorithm. If the spacing is to stay constant, then the algorithm might be something like “if local density too low, move toward beacon; if too high, follow the density gradient”, while if the diameter is to stay constant, it might be something like “if distance to beacon too large, move toward beacon; if too high, follow the density gradient”.

How to handle communications with the commander can also present a problem. Just as it is desirable for ensemble behaviors to be invoked by broadcasting a single message to all the participating elements, it would clearly be highly desirable for reports sent back to the commander to represent a fusion of the knowledge available to the numerous individual elements, and not have each element reporting on its own. This may imply a need for some hierarchical or heterarchical organization of the elements, not to facilitate command, but for reporting. Such an organization could be permanent, based on intrinsic differences between different castes of elements, or changeable, reflecting the roles that the different elements currently play (such as “on the edge”, in the simulated condensation behavior example).

5.0 FUTURE DEMONSTRATION AND IMPLEMENTATION

Credibility for this approach will ultimately depend on a demonstration of real physical behaviors using real physical robots. When funding permits, the plan is to use inexpensive "toy" vehicles, "clever" sensors, and a compact controller implementation to produce a demonstration of purposeful group behavior that can address a class of military applications.

One option is to develop an initial demonstration using an existing group of vehicles, such as the "Nerd Herd" of 20 IS Robotics R-1 indoor robots (weighing 4 pounds apiece) at the MIT Mobile Robots Lab. R-1s use Brooks's subsumption architecture, offer a very reasonable Macintosh-based software development environment, and the acoustic beacons that come with the system make the location of each R-1 known to all the units, so a demonstration of "pseudosensor" based behaviors should be fairly straightforward.

A second option is to develop and implement very low cost vehicles (target: less than $1K each, vice the R-1's unit cost of $5K) with appropriate sensor and processing capabilities capable of achieving an outdoor demonstration using several tens of elements over areas of hundreds of meters. One candidate technology for this task is Echelon Corporation’s "Local Operating Network" ("LON") paradigm. LON distributed control technology appears to offer a highly cost effective substrate for the implementation of very inexpensive autonomous elements, with projected costs for the processing components in the $2-$5 range, and RF modems under $10. Moreover, Echelon's firmware provides a full suite of communications protocols as well as primitives for control of sensors and effectors.

Ultimately, however, the development of this type of system will require resources at a scale beyond current 6.1 budgets -- the project must be focused to a single real world application (or a small set of related applications). One key goal of the simulation and modeling effort is therefore to identify good candidate real world military applications, quantitatively characterizing the required group behaviors (in terms of number of elements, inter-element spacing and motion parameters), and developing conceptual designs for intelligent robots that could satisfy them (including element sensor, effector, and processing requirements).

6.0 ACKNOWLEDGEMENTS

This work is supported by the Intelligent Systems Program of the Office of Naval Research, Computer Science Division. The author wishes to acknowledge stimulating and critical discussions with Alan Meyrowitz and Teresa McMullen of ONR, Marek Lugowski and Richard Blidberg of the UNH Marine Systems Engineering Laboratory, Lynne Parker, Maja Mataric, and Anita Flynn of the MIT Artificial Intelligence Laboratory, and Howard Moraff and Su-Shing Chen of the National Science Foundation.

7.0 REFERENCES

1. Flynn, A.M. "Gnat Robots (And How They Will Change Robotics)", **Proceedings of the IEEE Micro Robots and Teleoperators Workshop**, Hyannis MA, 9-11 November 1987. Also appeared in **AI Expert**, December 1987, p 34 et seq.

2. Freedman, D.H. "Invasion of the Insect Robots", **Discover**, March 1991, pp 42-50.

3. New York Times, January 1, 1991, pp 35-39.

4. Macedonia, R.M., and B. Sert. "Low Cost Mobility for Robotic Weapons", **AUVS-88, the Fifteenth Annual AUVS Technical Symposium**, San Diego CA, 6-8 June 1988.

5. Megatek Corporation, "CRICKET: A Novel LPI Communication Concept", Report R2017-003-IF-2, 30 September 1978.

6. Partridge, B.L., Pitcher, T., Cullen, J.M., and Wilson, J., "The Three-Dimensional Structure of Fish Schools", **Behavioral Ecology and Sociobiology**, vol 6, 1980, pp 277-288.

7. Van Olst, J.C., and Hunter, J.R., "Some Aspects of the Organization of Fish Schools", **Journal of Fisheries Research Board Canada**, vol 27, 1970, pp 1225-1238.

8. Reynolds, C.W. "Flocks, Herds, and Schools: A Distributed Behavioral Model (Proceedings of SIGGRAPH '87)", **Computer Graphics**, vol 21 (4), pp 25-34.

9. Langton, C.G., ed. **Artificial Life: The Proceedings of an Interdisciplinary Workshop on the Synthesis and Simulation of Living Systems**. Addison-Wesley, 1989.

10. Gage, D.W., and Pletta, P.B. "Ground Vehicle Convoying", **Advances in Intelligent Robot Systems: Mobile Robots II**, Cambridge MA, 5-6 November 1988.

11. Harmon, S.Y., and Gage, D.W. "Current Technical Research Issues of Autonomous Robots Employed in Combat", **Proceedings of 17th Electronics and Aerospace Conference (EASCON)**, Washington DC, 10-12 September 1984, pp 215-219.

12. Gage, D.W. "Security Considerations for Autonomous Robots", **Proceedings of Symposium on Security and Privacy**, Oakland CA, 22-24 April 1985, pp 224-228. Reprinted in **Computer Security Journal**, vol 6, 1990, pp 95-99.

13. Franks, N.R. "Army Ants: A Collective Intelligence", **American Scientist**, vol 77, March-April 1989, pp 139-145.

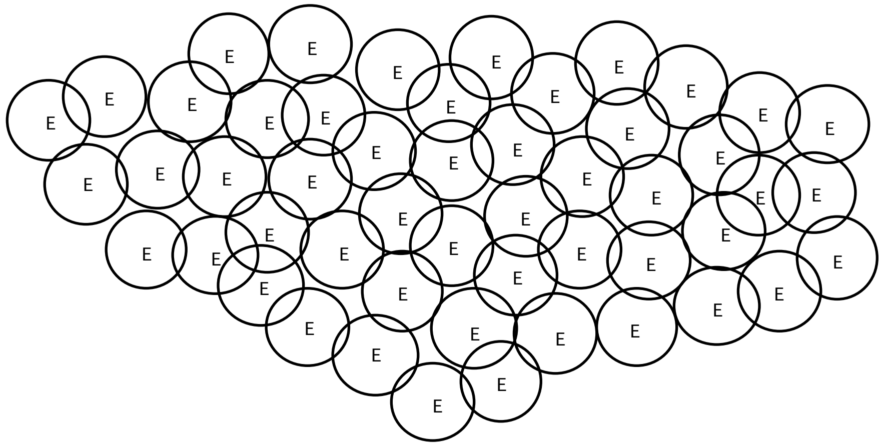
14. Deneubourg, J.L., et al. “The Dynamics of Collective Sorting Robot-Like Ants and Ant-Like Robots”, **Proceedings of First International Conference on Simulation of Adaptive Behaviors**, pp 356-363.

15. Seeley, T.D., "The Honey Bee Colony as a Superorganism", **American Scientist**, Volume 77, November-December 1989, pp 546-553.

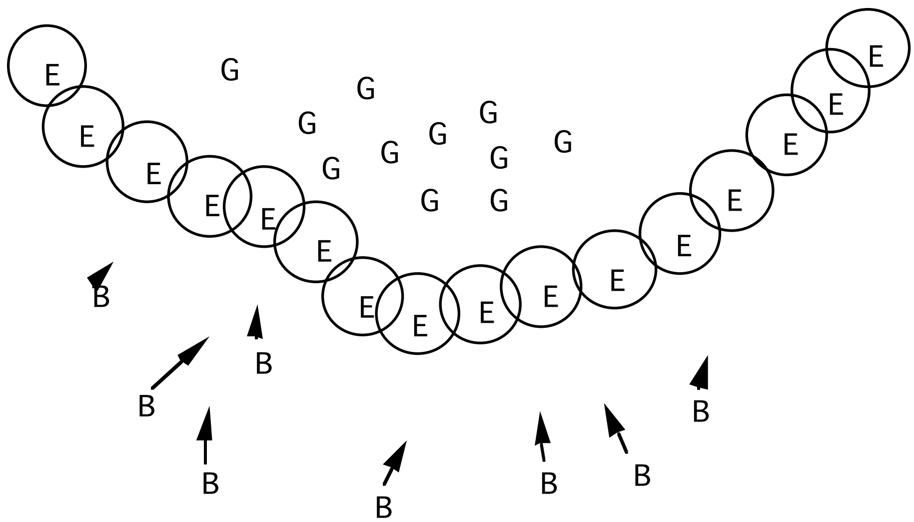
16. Braitenberg, V. **Vehicles: Experiments in Synthetic Psychology**, Cambridge: MIT Press, 1984.

17. Brooks, R.A. "A Robust Layered Control System for a Mobile Robot", **IEEE Journal of Robotics and Automation**, RA-2, April 1986, pp 14-23.

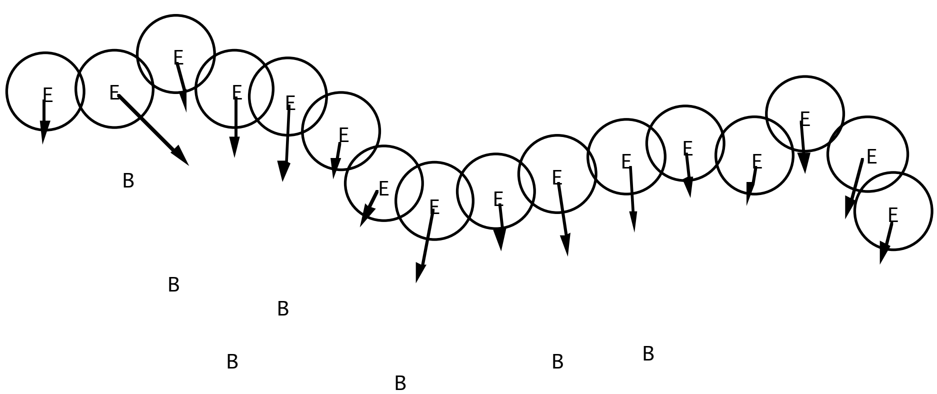
18. Sugihara, K., and Suzuki, I. “Distributed Motion Coordination of Multiple Mobile Robots”, **Proceedings of the 5th IEEE International Symposium on Intelligent Control**, Philadelphia PA, 5-7 September 1990, pp 138-143.



a. Blanket



b. Barrier



c. Sweep

Figure 1. Coverage Behaviors. E, G, and B represent system Elements, “Good guys” t be protected, and “Bad guys” to be engaged, respectively. The circles around system elements represent the effective sensor/effector engagement radius.

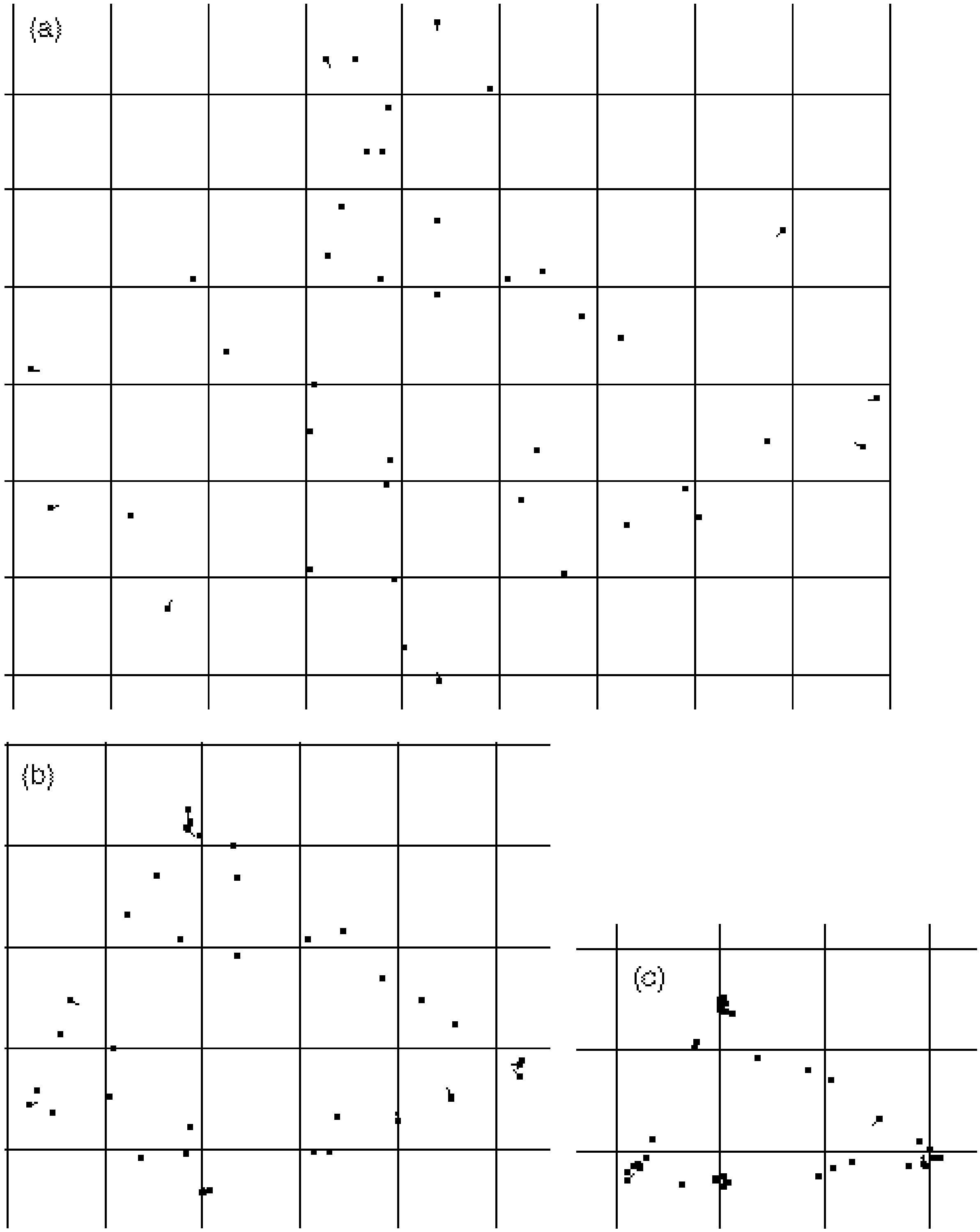


Figure 2. Simulation of “Condensation” algorithm. (a) First frame after algorithm has been initiated; element positions reflect random initial conditions. (b) 23 frames after first frame shown in a; group diameter is 42% smaller than when condensation began. (c) 27 frames after frame shown in b; note concentrations of elements at “corners” of configuration.