Dimensions of Communication and Social Organization in Multi-agent Robotic Systems

Ronald C. Arkin and J. David Hobbs
College of Computing
Georgia Institute of Technology
Atlanta, Georgia 30332-0280

Abstract

Communication, social organization, task type and complexity are defining characteristics of a multi-agent system. In this paper, extensions of schema-based reactive navigation are presented as a basis for constructing multi-robot societies. As has been our tradition, ethological studies provide significant insights into the way in which robotic systems can be structured. An analysis of relevant animal behavior, a delineation of the dimensions of multi-agent systems, a description of the overall project and simulation results to date constitute the body of this paper. The multi-robot testbed on which the results of this study will be deployed is also described.

1 Introduction

Multi-agent robotic systems hold tremendous potential for applications in hazardous and dynamic environments, especially in partially modeled or unmodeled worlds. Situations found in space exploration, undersea construction, nuclear waste management and reactor maintenance, all could benefit from the development of effective teams of robots coordinating their efforts towards a common goal. Typical problems would include such things as retrieval, simple construction tasks, routine cleaning and finishing, etc.

We have previously demonstrated [3] that cooperation between robotic agents is possible even in the absence of communication. Although teaming can occur under these conditions, it does not mean that the resultant work is necessarily efficient. There are many dimensions to the teaming of multi-agents that require significant additional study. These include the role and structure of communication in these systems, social structure and organization among the agents, the nature of the task to be accomplished, and the dynamics of the target environment.

This paper describes an on-going research project funded by the National Science Foundation on cooperation and communication in multi-agent reactive robotic systems. Our research has long been influenced by psychological, neuroscientific and ethological considerations [5,6,7]. This trend continues in our multi-agent study. Studies in animal behavior and communication provide models and insights that are being used to formulate implementations on real robotic hardware. It should be recognized that the goal of our research is to produce intelligent autonomous agents and not necessarily to be faithful to the biological models upon which much of our strategies are based [6,7]. To that end, we are less concerned with the biological fidelity of ethological models than their potential usefulness for extrapolation to robotic systems. We do not attempt to reproduce actual animal behavioral patterns, but rather look towards those systems for design inspiration (not replication) in our robotic systems.

This paper is structured as follows. Section 2 provides a brief review of related work in robotic multi-agent systems, followed by an overview of our schema-based (behavioral) methodology for robot control. Section 3 surveys relevant animal social behaviors and communication systems in this context. Section 4 describes the research effort and results to date and discusses the target hardware testbed using 3 Denning Mobile Robots. A Summary and Conclusions section completes this paper.

2 Related Robotics Research

The field of robotics is still largely concentrating on the issues of single agent performance. A limited number of researchers have performed some work in the area of multiple coordinated agents; this section reviews some of their progress to date.

Fukuda's pioneering work on multi-agent systems led to the development of the CEBOT system [17], a collection of heterogeneous agents capable of assembling themselves at run-time. A more recent paper [32] describes a hierarchical communication network between the disparate agents.

Mataric [23] is studying task performance in a population of twenty homogeneous mobile robots. Tasks such as homing, flocking, and puck gathering are being examined. This system is constructed within the context of the subsumption architecture, a behaviorally-oriented reactive system.

Beni and Hackwood [20] describe a multi-agent system which possesses the ability to redistribute sensing elements within a colony. Although not ported to a real robotic system yet, they indicate that future work regarding communication would enhance performance in their circulating swarm model.

Noreils has developed an architecture capable of supporting multiple mobile robots in hazardous environments [26] which has been implemented on two indoor mobile robots. The Gofer project at Stanford University [12] involves a more traditional planner using A* search to coordinate three indoor mobile robots over a road network. Sugihara and Suzuki [31] describe a simulation method for multiple mobile robots to achieve various formations. Miller [24] describes a potential application of multiple reactive robots for use in planetary surface missions.

This research area is progressing rapidly on many different fronts. The examples above are merely representative of the large body of on-going work in this field.

The schema-based approach for mobile robot behavior, developed in our laboratory, is reviewed below prior to its discussion in the context of multi-agent systems.

2.1 Schema-based Reactive Control

Schema theory [2] provides a fruitful methodology for implementing a behavior-based robotic system. This methodology, strongly influenced by work in cognitive psychology [28,29], has been developed into a modular behavior-based control system for mobile robots [4].

Motor schemas form the basis for all activity of the robot: each motor schema corresponds to a primitive behavior. A wide range of schemas has been developed including **move-to-goal, move-ahead, stay-on-path, docking, noise, avoid-static-obstacle, dodge, escape**, and so on. These and other behaviors are described in more detail in [4,8,9,10].

Each behavior is concurrently active, producing a single velocity vector in response to its perception of the environment. Perceptual schemas channel the requisite perceptual information for each motor schema to perform its task. This partitioning of perceptual activity on the basis of motor behavioral need is referred to as *action-oriented perception* [5]. Each individual vector is summed and normalized and the result transmitted to the robot for execution. This stimulus-response reaction ensures timely response to changing environmental conditions. Effective robot navigation has been demonstrated in a wide-range of domains including indoor office buildings, outdoor campus settings, manufacturing environments, and in simulation for undersea and aerospace applications and rough terrain [4,8,9,5].

For the sake of completeness, formulations for several of the motor schemas used in the simulation studies follow:

- **Move-to-goal**: Move towards a perceptually discernible goal.

  $V_{magnitude}$ = fixed gain value
  $V_{direction}$ = in direction towards perceived goal

- **Noise**: a random vector used for exploration and to circumvent certain problems associated with potential fields methods [4,14].

  $V_{magnitude}$ = fixed gain value
  $V_{direction}$ = random direction for a given time persistence

- **Avoid-static-obstacle**: A repulsion is generated by a detected barrier to motion:

$$V_{magnitude} = \begin{cases} 0 \quad for \quad d > S \\ \frac{S-d}{S-R} * G for \quad R < d \leq S \\ \infty \quad for \quad d \leq R \end{cases}$$

where:
S = Sphere of influence (radial extent of force from the center of the obstacle)
R = Radius of obstacle
G = Gain
d = Distance of robot to center of obstacle

$V_{direction}$ = along a line from robot to center of obstacle moving away from obstacle

Each active schema, at each point in time, generates a single velocity vector which is combined with the outputs of the other active schemas to yield the gross motion of the robot. No memory of the environment is involved at this level - the robot reacts to its immediate perceptions in a manner consistent with its goals. The net result is intelligent emergent navigational behavior.

3 Behavioral Aspects Relevant to Multi-Agent Systems

In order to produce effective multi-agent robotic systems we feel that it is important to study biological systems first. Insights gained through these studies can often be applied to robotic systems [5,6,7]. In particular, we look to ethological studies of communication and social organization in animal groups as potential models for multi-robot systems. Five particular areas are studied: system reliability, social organization, communication, multi-agent searching and coordination.

The intent of this study is to provide an understanding of both the dimensions of the solution space for task-achieving robotic societies, and indications of potential feasible solutions within that space. It is necessary to understand the variables which affect multi-agent performance. As has been our tradition, we first look towards biological system to provide a basis for our system development. The insights gained from these studies can assist in an efficient search of the multi-dimensional space involved in constructing efficient and effective multi-agent societies. This section, thus, details aspects of animal behavior which we believe to have potential utility in the design of multi-agent systems. This material is of necessity terse, and it should be recognized that it is presented from the viewpoint of a roboticist and not that of an ethologist. From a biological perspective, much has been boiled away or overlooked, but to a roboticist, these sample points can provide useful information as existence proofs of functioning multi-agent systems and to serve, to a degree, as design guidelines and avenues for experimental exploration in multi-agent robotics.

An overview of several different dimensions which can affect the design of multi-agent robotic systems follows.

3.1 System Reliability

System reliability, defined as the probability that the system can act correctly, is discussed by Wilson [34] regarding groups of ants. He draws the analogy between the design of parallel-series systems from engineering to the reliability of animal social systems. When a component fails in a series system, then the whole system fails. On the other hand, if a component fails in a parallel-series system, another component can take over. Wilson proposes a theorem that redundancy should be at low levels rather than at higher organizational levels. For instance, a more reliable system will emerge when individual robots rather than whole teams of robots are redundant.

Wilson also argues that the agents must perform above a certain competence level for working in groups to be beneficial. Basically, the agents must have a certain aptitude at working together for the teamwork to pay off. A trivial example is two robots which are trying to move the same item in two different directions. A more plausible problem would be two robots which are programmed to retrieve objects in mutually harmful ways, such as one robot lifting an object while the other attempts to drag it. If they do not have a certain competence at working together, then the overall reliability of accomplishing the task will be lower than if they were working individually.

3.2 Social Organization

A natural design decision involves how the agents should be organized. Animal societies are organized in many ways (Wilson has established 10 "qualities of sociality" and Deegener has defined over 40 categories of animal societies [33]). Social networks are one of the most natural ways for humans to think of social structures. The assignment of castes or types of agents is also a natural consideration.

There are several types of social structures in animals, including the multi-level, hierarchical structure of baboons [33], the uni-level structure of a fish school [33], and the loosely structured Whiptail Wallaby mob [21].[1] Animals without multi-level hierarchies are able to conduct activities of potential application for robotics. For instance, ants are able to build complicated structures, grow food, capture slaves, wage war, transport queens, and weave leaves without a strict and complicated hierarchy. The ants utilize a heterarchical structure where there are many castes but communication between the castes is unstructured. This heterarchy allows information to flow quickly, without having the information flow up and down chains of command [16,34].

Another issue is how many different types of agents exist within the social system. Wilson [33] states that if a contingency occurs regularly, that there should be a class of agents to handle this contingency. For instance, when building a lunar base, it may be better to have separate classes of builders and retrievers of appropriate materials. On the other hand, there must be a certain redundancy within each class for reliability to be high (Sec. 3.1).

Mode	*Directionality*	*Distance*	*Relevant Uses*
Audition	Low-Medium[5]	Far[6]	Alarm, Individuality
Luminescense	High[7]	Medium	
Chemical	Low[8]	Low[9]	Mass Communication
Reflected Light[10]	Medium	Medium	Social Distance [11]
Tactile	High	Low	
Electric	Low	Low	

TABLE I
SIMPLE COMMUNICATION

3.3 Communication

One of the most important measures of human's artificial communication systems is bandwidth (roughly, the amount of information conveyed). It appears that animals do not use a bandwidth anywhere near the range of modern day communication systems.[2] Mammals, birds, and fish have a very small range of "major displays" [27] (approximately[3] between 15 and 35). Typical ant colonies have between 10 and 20 signals [34].

Another important issue is the mode of communication. Animals use chemical, bioluminescence, reflected light, tactile, acoustic, echolocation, IR, and electric communication. Robotics and AI sensing research often stresses vision, but many animals are able to do several things with relatively simple visual systems. Table I summarizes the characteristics of some of these modalities, which can help designers choose a less expensive and more appropriate communication medium than vision.[4]

---

[1] Many prominent social structures are actually dominance systems ("pecking orders") which do not directly apply to robotic systems. In dominance systems, the more dominant agents have easier access to food, nesting sites, estrus females, freedom of movement, or roosting places. An example dominance system is among lions, where the dominant lions eat before the other lions. Lion cubs often die from this (by having weaker lions not reproduce, the overall strength of the species increases); robots need not compete at this level. Since the robots are not directly competing amongst themselves, these dominance systems are unnecessary.

[2] Vision may be a high bandwidth medium, but the amount of information conveyed is often small, e.g., flashing a red card may only convey one bit. Our visual system may have evolved so that we can extract information from the world when we do not share an active protocol with the world.

[3] Although the exact number of bits of communication may be inexact, the bandwidth is still extremely low. Each major display may be "graded", that is, an analog signal.

[4] For more complete information on the different modes and communication information on particular animals, see [30].

[5] The directionality depends on the frequency.

[6] There are design reasons for limiting the broadcast range. In animal systems, predators may hear the broadcast. In friendly environments, there may be a problem with noise.

[7] The receiver may know exactly where the sender is, but it may be more difficult for the sender to direct the message to the receiver.

[8] Except in constant wind conditions (where the scent can be followed), or where the scent is left on an object.

[9] Except in wind.

[10] One of the reasons that reflected light may be used by animals is because of "ritualization". Ritualization occurs when a normal animal activity, such as tugging at grass with teeth, is exaggerated in form to communicate something.

3.4 Multi-agent searching

It is a well-accepted fact that animals working in groups are more effective at foraging or hunting in certain circumstances. The relationship that seems most prevalent in animals and most applicable to robots is that between the distribution of the resource and the social structure of the animals. Some of the possible social animal configurations for food-seeking involve small versus large groups and overlapping versus non-overlapping foraging ranges. There appears to be a relationship between the density of the resource and the group size (more abundant resources correspond with larger group sizes) and the distribution of the resource and the searching range (the more restricted the more overlap) [1,13]. A group of agents would not necessarily have to forage together. For instance, according to Horn's principle of group foraging, if a resource is evenly distributed it may be better for birds to form individual partitioned territories rather than roost and forage together [33]. Useful models for ant foraging have also been developed [15,18].

In robotics, for any exploration task, the distribution of what needs to be located should be considered first to determine the search space and search groups. For instance, assume a robotic system is given the task to clean the hull of a ship. If the barnacles are uniformly distributed, it may be best first to have the robots distribute themselves evenly and then start cleaning. If the barnacles are dispersed and abundant, then larger teams should search disjoint spaces. In fact it may be best to have a different caste of robots determine what the distribution should be based on the species and age of the barnacles.

3.5 Multi-agent Coordination

Animals participate in many activities, sometimes alone, sometimes in groups, and sometimes in subgroups. These activities must be coordinated. An example is the whiptail wallaby [21], which belongs to a mob of 30-40 individuals, but grazes with dynamically changing sub-groups. Robots should also show a wide range of behaviors.

Finding each other becomes an issue when robots participate in a wide range of behaviors alone or in sub-groups. An obvious method of finding one another is to have a central meeting place. In animals, this becomes desirable for certain foraging strategies and for better defense. Lekking is a another method where a number of individuals of the same sex get together in a group and all make noise at the same time. This increases the chance of an agent hearing the location. Table II depicts these and other strategies. (The information center hypothesis referred to in the table states that colonizing birds use information from the incoming birds about where they will go next for food. The hypothesis is not universally accepted [19]).

The remainder of this paper discusses the framework in which many of these insights are being tested and developed.

Method	*When Useful*
Colony	Group Defense Information Center Hypothesis
Lekking	Multiple Agents looking for widely dispersed individual agents
Distinctive Call	Only certain agents can respond to find lost
Assembly Calls	Collect widely dispersed agents

TABLE II
SIMPLE COORDINATION

4 Project overview

The overall goal of this research is to develop a design theory for multi-agent robotic systems. Through the specification of a societal task and a particular environment, design recommendations should be available as to the number of agents that are required, the modes of communication necessary for reliable task achievement, and the social structure of the individual agents. By using an understanding of biological social systems, we expect to be able to converge on such a design theory more rapidly than would be attainable otherwise.

This section describes the first phase of an on-going NSF funded research effort in multi-agent robotics. Simulation results are presented below. The research underway involves an investigation of multi-robot systems along several different dimensions. These dimensions include the nature of communication between agents, the amount of communication between agents (bandwidth), the inter-relationships of agents (teaming effects), the nature of tasks (both simple and more complex), and the migration of the simulation results onto a working robotic system. Although these dimensions will be discussed separately in the sections below, it should be recognized that a holistic and/or synergistic effect is quite possible and the multi-dimensional space is being analyzed for such trends. The results are being evaluated in terms of task completion time, computational cost, efficiency in terms of overall utilization of resources, etc.

The simulation testbed described below provides the basis for expanding and enhancing these preliminary results prior to their migration onto working robotic systems. This testbed is an extension of the motor schema simulator system within which we test our research prior to actual robotic experimentation. It is a well developed and highly modular system that can support new schemas and communication mechanisms readily with little development overhead.

4.1 Dimensions of the Study

The project involves an analysis of the effects of communication, social organization, and task type and complexity for multi-agent robotic systems. Data points discovered in biological systems, such as discussed in Section 3, can facilitate the discovery of efficient solutions in this very complex solution space. Quantitative measures of system performance, in terms of time for completion, efficiency of completion, and other metrics (e.g., safety) are being applied to produce substantive evaluations between candidate systems.

4.1.1 Effects of Communication

It is perhaps most important to understand the impact of adding communication ability to these multi-agent units. It is crucial to determine the effects of the nature of information flow on task accomplishment. The variables include simplex or duplex communication, simple positional reports with or without acknowledgment of receipt, dynamic teaming arrangements via polling, and other more complex arrangements. The analysis is being conducted along the dimensions of direction of communication, quantity of information transmitted, broadcast or direct inter-agent communication, and specific inter-agent communication protocols.

4.1.2 Effects of Organization

Both inter-robot and intra-robot effects of organization are being studied. Intra-robot organization involves an assessment of the impact of non-symmetrical robotic agents. In the most severe case this includes pure master/slave relationships. Additionally, an analysis of how robots that possess different functional attributes (as with drones, workers, etc.) can cooperate and subdivide difficult tasks effectively forms an integral part of the overall project.

Inter-robot organization involves the impact of teaming: coordinated effort and communication between groups of multiple agents. These agents can be both symmetric and non-symmetric. The effect of team size is being assessed as well.

4.1.3 Effects of Task Type and Complexity

Thus far we have studied a simple retrieval task (below). Adding goal sequencing, something required for assembly-type tasks, is one simple extension being developed. More complex tasks such as maintenance of material flow throughout an organization, surveying, and simple construction also will serve as test scenarios for multi-agent robotics.

Other factors such as coordinated servicing (where two or more robots are required to complete a task such as a complex assembly), are also to be studied. The effects of such a *critical mass* of robots on task completion is to be analyzed in light of alternate control and communication regimes.

4.2 Simulation Results for Multi-agent Retrieval

Results have already been obtained showing multi-agent systems cooperating both in the absence of any inter-agent communication [3] and with simple communication mechanisms [25]. Three different schema assemblages have been developed representing forage, acquire, and deliver states (Fig. 1) for a simple target gathering task. Schema assemblages are aggregations of motor schemas that are parameterized to manifest an emergent behavior that is consistent with the particular state that the agent happens to be in. Much of our inspiration is derived from studies in ant behavior [15,16,18,34], although there is no attempt to simulate ant societies through this work.

An individual robot agent initially starts in a forage state, which consists of an assemblage of high-gain noise, moderate obstacle avoidance, and inter-agent repulsion. This assemblage of behaviors produces wide coverage of an area during search for an attractor object while avoiding collisions with sensed obstacles. When an attractor is sensed within some arbitrary range of the robot, it transitions to the acquire state. This state assemblage consists of a very low-gain noise, a move-to-goal schema directed toward the attractor object, and an avoid-static-obstacle schema (Section 2.1). Additionally the inter-agent repulsion is turned down significantly, allowing multiple agents to congregate in a small area. After acquiring the attractor object, the system transitions to the deliver state, which redirects the move-to-goal to the deposit location, leaving the other schemas in the assemblage the same as in the acquire state. The specific parameterizations for these assemblages appears in [3].

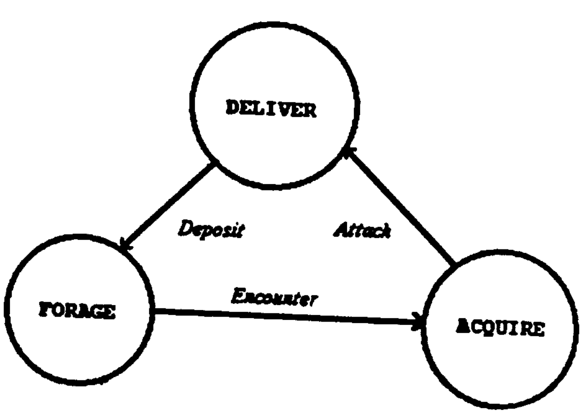

Fig. 1. Schema-assemblages for retrieval task

4.2.1 Retrieval in the Absence of Communication

The first phase of the study, involved developing an understanding of what could be accomplished in the absence of any inter-agent communication. Ants leave chemical trails to denote where they have been, which is an indirect communication mechanism. No such information was provided here - only what was immediately perceivable to the agent (nearby goals, close obstacles, and the presence of other robots) was available. Each agent had no knowledge of what the other agent was doing and operated completely independently.

It was observed, that even in the absence of communication, coordinated completion of the task of object retrieval is possible and surprisingly efficient. The phenomena of recruitment is observed as well, something often associated with communicating agents. Recruitment refers to the collective behavior of multiple agents working together to accomplish a common task. Figure 2 depicts one example where the robots collaborate in returning a target object. In this Figure, two independent agents start near the center, both in foraging mode. After a bit of wandering, the leftmost agent senses the attractor (light disk) behind the obstacle (dark disk). It proceeds towards it and starts to retrieve it. In the meantime,

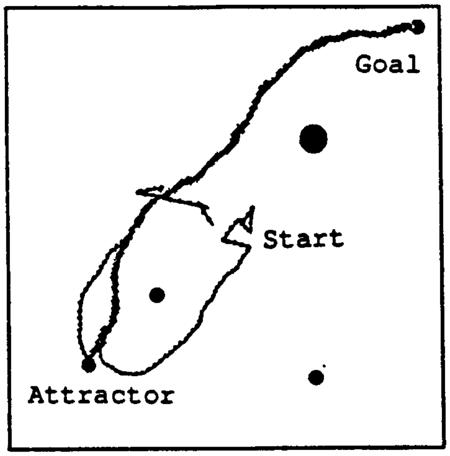

Fig. 2. Multi-agent simulation run showing retrieval of object. Dark circles represent obstacles, shaded circle is target object and goal is in upper right. (See text for explanation).

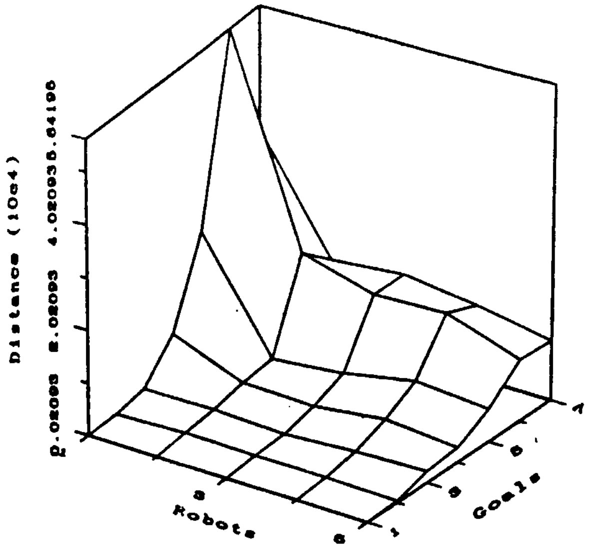

Fig. 3. Total Foraging Distance - No Communication, 10% Obstacles.

the other agent also senses the attractor. It joins the other agent in retrieving it, speeding up the return rate twofold.

Extensive simulation studies were performed to develop an understanding of the relationships between numbers of agents, numbers of goals, and system efficiency for particular environments. Several metrics have been developed reflecting speed, safety and efficiency. Figure 3 presents the total distance spent by the robots seeking out goals (foraging) for 1-5 robots retrieving 1-7 goals. This is one measure used to determine system efficiency. The more time spent foraging, the less efficient the system. The reader is referred to [3,25] for additional simulation studies.

4.2.2 Retrieval with State Communication

As discussed in Section 3.3, there are many ways in which agents can communicate with one other. The amount of information transmitted is an important consideration. As most of our research is geared for developing robots that can function in dynamic and hazardous environments, our studies have begun by exploring minimal communication methods and assessing the impact on system performance.

In the instance described here, communication between agents consisted merely of transmission of the state of the agent if it was in either retrieval or acquire mode. Under these circumstances, if an agent that was in forage state learned that a nearby agent was in acquire or retrieve state, it moved directly towards that agent. This was a more direct elicitation of recruitment. No knowledge of where the goal was given however, only the information that the communicating agent had discovered a target object. More efficient methods can be imagined such as the transmission of the coordinates of the attractor (e.g., bees), but that is not the case here.

Figures 4 shows simulation results acquired for various numbers of robots and various numbers of attractor objects when this form of communication is permitted. It can be seen that the simple communication mechanisms described above facilitate societal task accomplishment (this is the expected result). Although Figures 3 and 4 may look similar, the scales to which they are drawn are different, with the maximum value for Figure 4 being about 25% that of Figure 3, clearly illustrating the impact of even this minimal form of communication. These and other results are discussed in more detail in [25].

We intend to continue to explore alternate communication strategies including:

- Transmission of attractor coordinates when they are discovered.
- Directional versus non-directional communication.
- Communication strength.
- Distinctive signals for different actions.
- Certain types of robots being attracted to one another, and when a certain critical threshold is exceeded they call for all the other agents (assembly calls or lekking).

Reiterating, the goal of this project is to ultimately provide design guidelines for those developing multi-agent robotic systems in terms of numbers of agents, social organizations, and modes of communication. We are especially concerned with systems operating in hazardous environments where individual agents can be considered expendable. The biological studies discussed in Section 3 provide guidance for efficiently exploring the very large space of potential solutions.

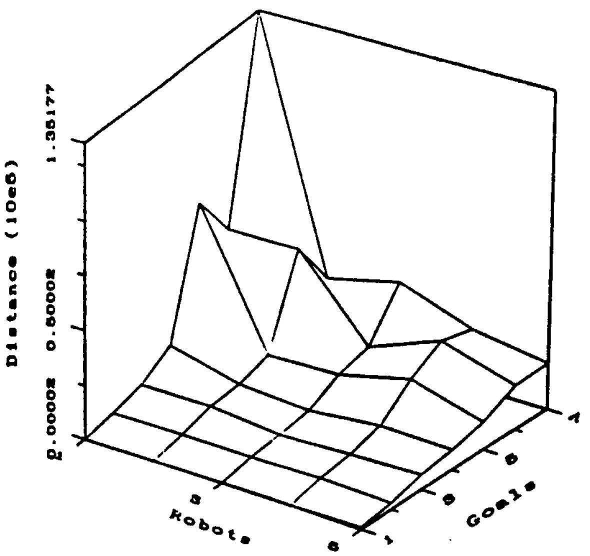

Fig. 4. Total Foraging Distance - State Communication, 10% Obstacles. Note change in scale of vertical axis from previous figure.

4.3 Hardware Configuration

The simulation work is in the process of being ported to 3 Denning Mobile Robots: two MRV-2's and 1 DRV-1. Each robot is connected to a Sun Sparc 4/40. In addition to the 24 ultrasonic sensors and shaft encoders mounted on each robot, a monochrome CCD Pulnix camera will be mounted on-board each. The cameras are to be mounted upwards and have a conic located immediately above the lens to provide a full 360 degree field of view for each robot [22]. A 19.2 kilobaud serial link using Lawn transmitters is used to maintain communication with the offboard hosts. A video link transmits the data for digitization by a Sun videopix board. Communication between the agents is conducted over ethernet.

5 Summary and Conclusions

This paper presents preliminary results from an on-going research project in multi-agent robotic systems. The relevance of ethological studies for application in this domain has been stressed and will be utilized as a guide for the development of a schema-based reactive system.

Preliminary simulation results are promising and provide solid ground for continuing work in exploring the dimensions of communication, social order, and task complexity for this work. Guidelines for the development of multi-agent robotic systems in terms of communication protocols, numbers of agents, and their structure will be a major product of this research. The system is being ported to real mobile robots for testing.

It must be remembered, that the perspective and goals of this paper are those of a roboticist, not an ethologist. No claims are made for the completeness of the ethological material presented. Nonetheless, these data points have been very helpful in determining our approach to designing multi-agent robotic systems. It is hoped that continued studies and additional interactions with colleagues in the biological sciences will provide further insights and models for potential application in robotic systems such as these.

Acknowledgments

The Mobile Robot Laboratory is supported in part by the National Science Foundation under grants #IRI-9113747 and #IRI-9100149, and the CIMS program and Materials Handling Research Center of Georgia Tech. The authors would like to thank Elizabeth Nitz for her generation of some of the simulation results used in this paper.

References

[1] Altmann, S.A., "Baboons, space, time, and energy", *American Zoologist*, 14:221-248, 1974.

[2] Arbib, M.A., "Schema Theory", article to appear in *Second Edition of Encyclopedia of Artificial Intelligence*, 1992.

[3] Arkin, R.C., "Cooperation without Communication: Multi-agent Schema Based Robot Navigation", *Journal of Robotic Systems*, Vol. 9(3), April 1992, pp. 351-364.

[4] Arkin, R.C., "Motor Schema-Based Mobile Robot Navigation", *International Journal of Robotics Research*, Vol. 8, No. 4, August 1989, pp. 92-112.

[5] Arkin, R.C., "The Impact of Cybernetics on the Design of a Mobile Robot System: A Case Study", *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 20, No. 6, Nov/Dec 1990, pp. 1245-1257.

[6] Arkin, R.C., "Neuroscience in Motion: The Application of Schema Theory to Mobile Robotics", chapter in *Visuomotor Coordination: Amphibians, Comparisons, Models, and Robots*, ed. P. Evert and M. Arbib, Plenum Publishing Co., pp. 649-672, 1989.

[7] Arkin, R.C., "Modeling Neural Function at the Schema Level: Implications and Results for Robotic Control", chapter to appear in *Biological Neural Networks in Invertebrate Neuroethology and Robotics*, ed. R. Beer et al, Academic Press.

[8] Arkin, R.C. and Murphy, R.R., "Autonomous Navigation in a Manufacturing Environment", *IEEE Transactions on Robotics and Automation*, Vol. 6, No. 4, August 1990, pp. 445-454.

[9] Arkin, R.C. and Gardner, W., "Reactive Inclinometer-Based Mobile Robot Navigation", *Proc. of 1990 IEEE International Conference on Robotics and Automation*, Cincinnati, OH, pp. 936-941.

[10] Arkin, R.C. and Carter, W.C., "Active Avoidance: Escape and Dodging Behaviors for Reactive Control", *Proc. Applications of Artificial Intelligence X*, Orlando, FL, April 1992, pp. 676-688.

[11] Box, H.O., *Organisation in Animal Communities*, Butterworth, 1973.

[12] Caloud, P., Choi, W., Latombe, J., LePape, C., and Yim, M., "Indoor Automation with Many Mobile Robots", *1990 IEEE International Workshop on Intelligent Robots and Systems (IROS90)*, pp. 67-72.

[13] Carr, G.M. and MacDonald, D., "The Sociality of Solitary Foragers: a Model Based on Resource Dispersion", *Animal Behavior*, 34:1540-1549.

[14] Clark, R.J., Arkin, R.C., and Ram, A., "Learning Momentum: On-line Performance Enhancement for Reactive Systems", *Proc. 1992 IEEE International Conference on Robotics and Automation*, Nice, France, May 1992, pp. 111-116.

[15] Deneubourg, J.L. and Goss, S., "Collective Patterns and Decision-making", *Ethology Ecology and Evolution* 1: 295-311, 1989.

[16] Franks, N., "Teams in Social Insects: Group Retrieval of prey by army ants", *Behavioral Ecology and Sociobiology*, 18:425-429, 1986.

[17] Fukuda, T., Nakagawa, S., Kawauchi, Y., and Buss, M., "Structure Decision for Self Organising Robots Based on Cell Structures - CEBOT", *IEEE International Conference on Robotics and Automation*, Scottsdale Arizona, pp. 695-700, 1989.

[18] Goss, S., Beckers, R., Deneubourg, J., Aron, S., and Pasteels, "How Trail Laying and Trail Following Can Solve Foraging Problems for Ant Colonies", *Behavioral Mechanisms of Food Selection*, ed. Hughes, R., NATO ASI Series, Vol. G20, Springer-Verlag, 1990.

[19] Gotmark, F., "A Test of Information-centre hypothesis in a colony of sandwich terns *sterna sandvicensis*". *Animal Behavior*, 39:487-495, 1990.

[20] Hackwood, S. and Beni, S., "Self-organization of Sensors for Swarm Intelligence", *1992 IEEE International Conference on Robotics and Automation*, Nice, pp. 819-829.

[21] Kaufmann, J.H., "Social Ethology of the Whiptail wallaby, *macropus parryi*, in northeastern New South Wales", *Animal Behavior*, 22:281-369, 1974.

[22] MacKenzie, D. and Arkin, R.C., "Autonomous Helicopter Position Determination using an On-board Integrated Vision System", *Proc. SME/MVA Applied Machine Vision Conference '92* Vol. I, Atlanta, GA, June 1992.

[23] Mataric, M., "Minimizing Complexity in Controlling a Mobile Robot Population", *1992 IEEE International Conference on Robotics and Automation*, Nice, pp. 830-835.

[24] Miller, D.P., "Multiple Behavior-Controlled Micro-Robots for Planetary Surface Missions", *Proc. 1990 IEEE SMC Conference*, Anaheim, CA.

[25] Nitz, E. and Arkin, R.C., "Communication of Behavioral State in Multi-Agent Retrieval Tasks", submitted to *1993 IEEE International Conference on Robotics and Automation*, Atlanta, GA, May 1993.

[26] Noreils, F.R., "Multi-Robot Coordination for Battlefield Strategies", pre-publication manuscript from author.

[27] Moynihan, M., "Control, suppression, decay, disappearance, and replacement of displays", *Journal of Theoretical Biology*, 29:85-112, 1970.

[28] Norman, D. and Shallice, T., "Attention to Action: Willed and Automatic Control of Behavior", from *Consciousness and self-regulation: Advances in research and theory*, 4, p. 1, (R. Davidson, G. Schwartz, and D. Shapiro, eds.), Plenum Press, New York, 1986.

[29] Neisser, U., *Cognition and Reality: Principles and Implications of Cognitive Psychology*, Freeman, 1976.

[30] Sebeok, T., Ed., *How Animals Communicate*, Indiana University Press, 1977.

[31] Sugihara, K. and Suzuki, I., "Distributed Motion Coordination of Multiple Mobile Robots", *1990 IEEE International Conference on Robotics and Automation*, pp. 138-143.

[32] Ueyama, T., Fukuda, T., and Arai, F., "Configuration of Communication Structure for Distributed Intelligent Robotic System", *1992 IEEE International Conference on Robotics and Automation*, Nice, pp. 807-812.

[33] Wilson, E.O., *Sociobiology: The New Synthesis*, Belknap Press, 1975.

[34] Wilson, E.O., *The Ants*, Belknap Press, 1990.