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How to communicate with zillions of robots

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ABSTRACT

This paper discusses some communications issues relevant to a system consisting of an arbitrarily large number of simple autonomous robots, from several different perspectives: (a) in the language of traditional communications systems analysis, (b) by analogy with biological systems, and (c) as a problem of intelligent control and data fusion. Emphasis is placed on support for the system development process: providing the developer with the ability to efficiently download software revisions and to determine the actual internal behavioral states of system elements while in operation. Also treated are the need to support coordination (or at least cooperation) between elements during system operation, and the process by which an external user can input commands to the system and to receive back from the system such information as system status, environmental characterization, and indications of mission progress. An approach to implementation of a low-cost testbed environment is also presented.

1. INTRODUCTION

The rapid evolution of micromechanical fabrication techniques and other enabling technologies suggests that systems consisting of large numbers of simple autonomous robots may soon provide an appropriate solution to many real world applications [1]. If, as appears plausible, planar integrated circuit fabrication techniques can be adapted to manufacture complete functional robots (of even limited capabilities) at extremely low cost, then the numbers of such elements employed in a single system could be extremely large. For example, the cost of a single cruise missile could instead buy literally millions of fifty-cent robots.

Nature provides outstanding models of functioning systems consisting of large numbers of more or less intelligent and mobile elements. Flocking, herding, and schooling behaviors are observed in many different types of vertebrates, and even more interesting are the aggregate behaviors of the social insects -- ants, bees, and termites, which exhibit greater complexity, even though individual insects are much simpler than vertebrates. Through experimental manipulation of insect colonies and computer simulations, researchers have elucidated some of the mechanisms which these colonies employ to survive and grow by adapting to their changing environment. For example, Deneubourg [2] has demonstrated via simulation that sorting behaviors observed in ants can be produced by the simplest possible biasing of random behavior by environmental cues, while Franks [3] has used simulation to explore the changing raiding patterns of army ants. Seeley [4] has investigated how worker honey bees appropriately initiate 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.

With various individual and group animal behaviors serving as "existence proofs", quasi-intelligent "emergent behavior" resulting from the interaction of simple reactive planners has been proposed as the basis for the intelligent control of individual robots, in the development of usefully complex systems [5] as well as simple conceptual vehicles [6]. The term "Swarm Intelligence" has been used to describe the application of this approach to distributed systems consisting of perhaps hundreds of elements [7,8]. Biological models are explicitly acknowledged as the motivation for much of this work [9,10].

In previous papers [11,12,13] we have developed (a) the notion of “coverage” as a paradigm for the system level functionality of many robot systems, (b) some initial notions of sensor-based behaviors to implement various coverage modes, and (c) measures of effectiveness and system design considerations for the generic area search application (e.g., minesweeping). This paper discusses some communications issues relevant to a system consisting of an arbitrarily large number (hence the “zillions” of the title) of simple autonomous robots. In Section 2 we examine some standard constructs for analyzing communications systems, and develop the concepts of cueing and display as an alternative language for describing the "communications" supporting cooperative group behaviors of both natural and artificial many-element systems. Section 3 defines a many-robot system's conceptual requirements for both peer-to-peer and hierarchical communications. We propose a set of generic communications mechanisms to satisfy these requirements in section 4, and discuss many-robot system communications testbed issues in section 5.

2. COMMUNICATIONS CHANNELS, PROTOCOLS, AND CUEING

The standard analysis of artificial communications systems is based on the abstraction of the *communications channel* as a means for conveying messages from an information source to a destination. The power of this abstraction in supporting analyses of such communications system parameters as bandwidth, signal to noise ratio, entropy, and maximum signalling rate is due to the fact that the abstraction ruthlessly disregards all issues not relevant to a physical communications channel. To quote from Claude Shannon's seminal 1948 paper, which served as the cornerstone for the development of information theory:

> "The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point. Frequently the messages have *meaning*; that is they refer to or are correlated according to some system with certain physical or conceptual entities. These semantic aspects of communication are irrelevant to the engineering problem. The significant aspect is that the actual message is one selected from a set of possible messages." [14]

The development of packet switched networking in the late 1960s and its subsequent blossoming into today's multi-million node and exponentially growing Internet has been possible only because this "bits is bits" view has been augmented to ensure that a message transmitted by one type of system can be correctly dealt with by another type of receiving system -- the ISO Open Systems Interconnection Reference Model [15] provides a seven layer protocol "stack" structure to represent the assumptions about what is being communicated that must be shared by transmitters and receivers of information in a heterogeneous network, and many specific protocols implementing different layers of the stack are now in wide use.

What is the relevance of these mainstream data communications paradigms to systems consisting of very large numbers of simple autonomous robotic elements, or to the biological systems which motivate the artificial systems' development? It is certainly possible to describe animal communications in terms of bandwidth [9], but is it really useful? One alternative approach is to consider a robot's communications transmitter and receiver subsystems as specialized effectors and sensors, respectively. A transmitter clearly must affect some property of the robot's environment if it is to transmit a detectable signal, and a receiver must clearly sense some property of the environment in order to receive information. What makes communication a powerful abstraction is the cooperative mode of interaction between transmitter and receiver, and the assumptions shared by information source and destination about the information being conveyed. Communication, in fact, represents one end of a spectrum of possible modes of operation of one element's effectors with respect to another element's sensors (assuming that the effector's actions are detectable by the sensor, which is not necessarily the case):

> Cooperative modes: (1) facilitate measurement by the sensor (e.g., provide a beacon to support detection and localization), and (2) modulate parameter measured by sensor (communication);
>
> Neutral mode (operate effector without regard for sensor); and
>
> Adversarial modes: (1) avoid measurement by the sensor, and (2) induce misleading measurements (spoofing; see [16] for further consideration of these adversarial modes, and of the security aspects of autonomous robotic systems).

Communication is a <u>deliberate</u> act, but this element of deliberation is often missing from the "cooperative" interactions of simple animals. A more appropriate terminology might be in terms of "cues" and "displays". Given appropriate context, a specific behavior of one element can *cue* a specific behavior in another element, and this can happen whether or not the transmitter of the cue intends to affect the behavior of the receiver -- the cueing behavior may be the element's natural response to the specific situation regardless of the presence of other elements. As an example, a lone foraging bird may fly away if it detects danger; when it is in a flock, however, its flight may well trigger the flight of the other birds.

A cueing action is often not instantaneous; rather, there is some finite (and perhaps very long) time interval during which the cue can be interpreted by a sensing element, and the same response will be elicited no matter when the receiver senses the cue. The transmitter of a cue does not deliberately modulate the "channel" to send serial messages, although in theory any effector-sensor interaction could be exploited as this sort of traditional channel, given the establishment of a suite of protocols agreed upon in advance by transmitting and receiving elements. Instead, the information conveyed by the cue is essentially that the transmitter is in some particular significant state, relevant to the overall scheme of "system control". This mechanism of exchanging low-bandwidth behavioral state information has been explored in simulation and found to be effective in coordinating group behaviors by Arkin et al [17] and Lucarini et al [18].

A deliberate cue -- that is, a state-based (as opposed to message-based) cueing action whose sole purpose is to trigger behavior in other elements -- could be called a *display*. In some cases a display might be a simple elaboration of an action being taken anyway. For example, the person at the helm of a yacht maneuvering to avoid another yacht should make <u>decisive</u> changes of course so that the person at the other helm will understand his/her intentions.

In many cases, the relevant "message" of a received cue is simply knowledge of the cueing action itself -- "I am changing my course to port". In others, it is an implicit "message" which controls the cooperative behavior -- "(I'm flying away because) I have seen a hawk" or "(It's taking me so long to come take the nectar from you because) the hive is so full of honey that I can't find a place to put the last load" [4].

When designing a many-robot system, we should do what Mother Nature has done with biological systems: ruthlessly exploit the opportunities presented by each sensor and effector resource we decide to build into the system. Cooperative modes of effector/sensor interaction are cost effective from a systems viewpoint. It is important to note, too, that an <u>explicit</u> cue display mechanism may be especially valuable in artificial systems because a robot's perceptual capabilities may not be adequate to classify other elements' inadvertant behavioral cues. Other possible cooperative (but clearly non-communication) effector-sensor interaction modalities that can be exploited include mechanisms as complex as multistatic radar or as simple as detecting intruders by observing the eclipse of a beacon mounted on another element.

Of course, while many effective cooperative behaviors have evolved or can be designed using any number of variations on the cueing and display theme, other behavioral interactions may indeed be best thought of in communications terms. An outstanding example from insect societies is the "dance" of the honeybee, in which the dancer modulates her direction and wiggle-speed in order to convey quantitative parameters describing a food source.

3. SYSTEM COMMUNICATIONS REQUIREMENTS

The general requirement for all the communications techniques we are attempting to define is that they should be applicable to systems comprising an <u>arbitrary</u> number of interacting elements. LAN buses capable of supporting a limited number of nodes and sequential polling techniques whose access time increases linearly with the number of elements are only two of many conventional communications techniques that can not be used in such a system.

3.1 Peer-to-peer Cooperation

Cooperative behaviors can often be realized without communications of any sort between the elements of the system [19], and, as the discussion of Section 2 implies, simple cueing can be both effective and efficient when coordination of the overall system is to be based on some sort of information flow between peer elements. Message-based communications should be the exception in many-robot systems, just as it is in complex animal societies. In any event, communications per se should only be needed between elements that are nearest each other. This implies the use of signals of limited range -- on the order of a few times the distance between nearest neighbors. It would make sense to adapt the signal strength to maintain this contact while minimizing channel congestion.

3.2 Hierarchical Communications

For the foreseeable future, all many-robot systems will involve hierarchical communications.

Any artificial system must ultimately serve the desires of an external user, even a "swarm system" in which a large number of identical simple elements function purely as peers. As a system is deployed, it may be necessary for the user to pass mission parameters to the elements. Many systems will have to afford the user the means to update mission parameters during the mission, or to recall the system completely. Similarly, many missions will require the return of information from the system to the user or to other external entities.

More critically, while the deployment and operation of a given many-robot system may require no communication with the user at all, the process of <u>developing</u> it will require communications between the system and its developer in order to support the refinement of behaviors and/or algorithms. The many-element biological systems such as ants and bees which serve as models for our artificial systems have evolved through countless generations; it is certain that our own development efforts will require lots of tuning to achieve effective and efficient results. While simulation will play a major role in this system tuning, it will always be necessary to experimentally verify the validity of the simulation results, especially since simulations employing space and/or time granularity are especially vulnerable to computational artifacts [11,20]. Thus it is likely that the developer will still have to experimentally explore a many-dimensional behavior design space to ensure system effectiveness over as wide a range of application environments as possible. And it will simply not be possible to download a software update to one element at a time when there are potentially thousands of elements, especially during a behavior debugging process requiring many such software iterations. Similarly, while the ability for the developer to determine the internal state of specific system elements (i.e., what behaviors are actually operative) will be key to effective and efficient system tuning, behavior which appears visually to be "seamless" may in fact result from continuous rapid oscillation between different behaviors in a subsumption [5] or schema-based [9] architecture. Intelligent program management dictates accepting the increased up-front cost of an effective communications scheme between development engineers and the system elements in order to reduce program technical risk, schedule risk, and overall cost.

3.3 Mission-specific Communications

In addition to the communications requirements of a generic many-robot system, some applications will require that additional communications capabilities be incorporated into the system, for example, communications relaying [21]. These additional communications functions may coexist independently, or their interaction may provide either opportunities (e.g., resources that can be shared) or additional challenges (e.g., RF interference, bandwidth allocation) to the systems developer.

4. PROPOSED COMMUNICATIONS MECHANISMS

Rather than first focusing the development of a many-robot system on the mission-specific capabilities of the individual elements, and then glueing these elements together with an "afterthought" communications scheme, it is proposed to first develop communications capabilities that will satisfy the communications requirements of both system development and operation as outlined in the last section, then tie a number of fairly rudimentary elements together using these communications capabilities, and finally enhance the capabilities of the elements to satisfy the requirements of the application. Here are some generic communications mechanisms that could be utilized:

Broadcast Control Channel

A conventional relatively high bandwidth, low error rate broadcast channel is employed for communications from the "master" (the system user, user-proxy, or developer) to the "slaves" (individual elements). Appropriate error detection coding is applied to the channel, with error correction capability also desired since the large number of slaves precludes the general use of negative acknowledgements (NAKs) as well as positive (ACKs). Security measures (e.g., encryption) are appropriate to the application. A "keep-alive" protocol is employed (at least during development) -- even in the absence of anything substantive to say, the master transmits periodically, so that each element can be sure that it is receiving any messages transmitted by the master. A protocol is implemented for "almost reliable" downloading of software -- each block is transmitted redundantly (multiple transmission of each block, but no ACKs or NAKs), and old software is not discarded until the new code has been completely validated. The operating philosophy of this control channel is that, while it is likely that some elements may fail to receive any given message, they will be able to recognize this situation, and will be programmed to behave appropriately.

Cue Display Channel for Behavior Coordination and Status Reporting

Each robotic system element incorporates a low bandwidth display mechanism for sharing state information with its neighboring elements and/or its master. This mechanism might be, for example, a set of several different colored lights. The master assigns (and can dynamically reassign) a specific representational meaning to each light or combination of lights; coded modulation of the lights is not used to send serial messages. In a deployed system, each element may inform its neighbors of its own behavior state in order to more effectively coordinate the behavior of the local group. When a low cost "early warning" sentry robot detects an intruder, it can signal that fact to attract the attention of a more capable assessment and response robot (analogous to the action of antibodies and phages in the immune system). A system developer can program a light to represent a specific boolean combination or sequence of behavior states, in order to help understand an unexpected group behavior. Programmed sequences of display lights can be used to implement the highly desirable "please answer if you don't receive this message" function, allowing the culling of failed units (this may require inclusion in the display of one light which is always illuminated).

Data Fusion

One key benefit of using a display mechanism such as colored lights which can be directly imaged with a camera is the automatic aggregation and display of status and reporting information at the master. Instead of the master having to process an endless torrent of digital messages containing state information, maintaining a database containing each element's position and status, and repeatedly updating a display, the master can simply program a rapid sequence of display light assignments and use simple image processing to derive the desired information. The human user of a sentry system deployed in and around around a storage yard could use a camera on an aerostat to visually see where the robots are and what they "think" is happening. On a smaller scale, the elements of a distributed instrumentation system could be glued to the side of a piece of equipment and a camera set up to provide a continuous display of thermal, acoustic, or other parameters. And microsopic sized sensing elements programmed to change their optical characteristics in response to their chemical and/or physical environment could be suspended in a container of liquid to provide "in-situ visualization" of temperature, pH, or salinity.

Modulated Retroreflector

The systems of "gnat" sized and (potentially much) smaller robots that MEMS (microelectromechanical systems) technology may ultimately make feasible will involve additional communications difficulties. Severe power limitations will probably preclude the use of actively powered transmitters over any significant distance, including the display of lights proposed above. One option (which has been proposed several times in the past, at least as early as 1977) is to incorporate a modulated retroreflector into the "slave" units. The active node (master) illuminates the passive nodes with a laser beam, and the passive nodes modulate the signal which is retroreflected back to the active node. The carrier beam can be directly modulated for half-duplex operation, or two modulated subcarriers can be employed to provide full-duplex communications. This scheme allows the active node (the master) to provide all the power for communications in both directions. In addition, the passive nodes do not require a precise pointing system to achieve this high signal gain. The development of a standard cell MEMS modulated retroreflector would be a valuable addition to the microrobot toolbox.

Element Designation

A final proposed communications mechanism is the ability to "mark" or "address" individual robots or localized groups of robots by laser or other means. Each element incorporates a simple photosensor that continually indicates whether it is being illuminated by a designation laser. When a "mark" command is broadcast over the control channel, all currently illuminated robots assign themselves a specified address so that future messages can be easily sent to them.

Support for Multi-Level Hierarchy

Some applications will be best served by a multi-level hierarchy of elements. The system may be organized geographically, with a number of specialized elements serving as "centurions", each acting as a local master for the simple elements in its local area, and serving as a slave in turn to the system user. Assuming relatively homogeneous and isotropic control channel propagation, compactly shaped subareas, and adaptive selection of minimum required transmission power, then (by the four color theorem) four broadcast command channels should suffice to handle each communications level, independent of the total number of regions.

5. TESTBED ISSUES

It is clear that this paper has sketched only the general features of the proposed approach to many-robot system communications. The scheme will have to be fleshed out and refined before it can be applied to a real system. An experimental testbed would serve this purpose, and also provide a demonstration of the viability of the approach. The focus of the development of the testbed would be on the software aspects of the comunications system, since the specifics of the communications hardware will vary greatly between different real world applications. The issues to be explored would include: reliable program downloading, command issuance, sensor fusion and reporting, self-organization, and software version control. Selection of appropriate error detection and correction coding, protocols for software downloading, and an initial cut at a generic control language for using cue display would result from the initial work.

The key constraint on implementing such a testbed is the same as that for many-robot applications: robotic elements inexpensive enough to be implemented in quantity. Since the testbed development will not provide an immediate payoff to a specific application system, it will have to be very inexpensive. The elements could be as simple as small non-mobile circuit boards containing Echelon Neuron processors, multiple colored LEDs, and photocells, with simple phone wires (RJ-11 jacks/plugs) distributing power as well as a 1 Mbps twisted pair local area network (the maximum rate for Echelon). The Echelon processors are very inexpensive, having been developed to support applications such as smart light fixtures.

The testbed effort would be focused by addressing a high level task, such as tracking an “intruder” by using cooperative lidar (an intruder blocks various light paths as he moves through the field of elements spread out on the floor of a big dark room). Evolving self organization will be attempted in dynamic partitioning of the network (who-can-hear-who communications limitations will be implemented via table lookup, while light transmission will be limited by a "terrain" of cardboard barriers). The goal will be to get the per-element cost well below $100, so that systems of upwards of 100 elements will be very affordable.

The second phase of the testbed would introduce mobile elements based on toy cars, plus simple sensors and the Neuron-based control developed in the first phase. Short range radio (or perhaps infrared) would carry the master control channel. This system would need multiple “feeding troughs” for recharging large numbers of elements. This phase would explore issues of continuing situated operation, such as detection and removal of failed elements, deployment, recall, etc.

6. CONCLUSION

Communications will play an important role in the development of any many-robot system, if not in its deployment and operation, since effective communications between the developer and the system elements is a key prerequisite for the tuning of system performance and the achievement of functionality based on cooperative element behaviors. On the other hand, some systems applications will require no communications between peer elements, and rudimentary display of cues will suffice for many others. A set of generic communications tools have been proposed, and the role of a low-cost many-robot testbed in validating this approach has been outlined.

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