Bioinspired Environmental Coordination in Spatial Computing Systems

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***Abstract*—Spatial computing systems are characterized by the extended physical environment in which they exist and function. Often this environment can be manipulated in various ways by the computing agents. We argue that it is important to consider the potential use of the environment for coordination and indirect communication in such systems. For inherently spatial problems, it can be more effective to store spatially relevant information in the environment rather than in the computing devices, as in the case of mobile agents or long-term physical structures. In scientific settings, considering the role of the environment can illuminate mechanisms or processes that might otherwise be overlooked; in engineering problems, it can provide simpler and more effective solutions than could be achieved by relying on the computing devices alone. We give as examples problems related to foraging, collective construction, simultaneous localization and mapping, object tracking, and behaviors of living tissues. We suggest in closing a classification scheme for capabilities of environmental elements, relevant to the design of physically embodied spatial computing systems.**

I. Introduction

Spatial computing systems are distributed systems of computing agents that exist in a physical space, where the capabilities of the agents and the function of the system are both tightly linked to their being physically distributed. Examples of such systems include teams of mobile robots and tissues composed of multiple living cells; by contrast, local computer networks are not spatial computing systems, since they are constructed so that the physical nature of the network is independent of its function.

Although spatial computing systems are often characterized in terms of the individual computing devices and their relationships, these devices also may be influenced by the physical environment in which they exist. Here we use the term "environment" to refer to all physical elements of the system that are not the computing agents themselves. The main focus of this article is to explore the role that the environment can play in coordination and control of spatial computing systems, and to outline a classification scheme for capabilities of environmental elements that we hope will aid the future study and design of such systems.

This principle of indirect coordination mediated through the environment can be important both to scientific understanding of natural systems and to engineering of artificial ones. In the former case, broadening one's frame of reference when analyzing a system to include elements of the environment can be crucial to a full and accurate understanding of that system, if its operation relies on such elements. In the latter case, taking advantage of the environment can sometimes make it easy to solve otherwise very difficult problems, particularly explicitly spatial ones where the physical nature of the system can be leveraged.

In this workshop paper, we briefly review several examples of spatially distributed systems where the active use of environmental elements can be key to their operation. These include: natural and artificial swarms performing foraging (§II) and collective construction (§III), simultaneous localization and mapping for mobile robots (§IV), tracking of lost objects (§V), and living tissues composed of individual cellular components (§VI). In §VII, we propose a classification scheme for kinds of environmental information that may be harnessed for coordination and control of spatially distributed systems.

II. Foraging

One of the most famous examples of environmentally-mediated coordination is the pheromone trails laid down by foraging worker ants [1]–[3]. When these insects find a food source, they leave chemical trails during their return to the nest; other ants follow the trail, helping to recover the food and reinforce the trail to recruit still others. When the food is depleted, ants stop depositing pheromones, and the chemical fades over time. This coordination process allows ants to collectively choose and dynamically update routes that are favorable in various respects (e.g., minimizing travel distance to an energy source).

Artificial systems inspired by these natural ones have been constructed, using pheromone-like mechanisms to coordinate the foraging behavior of multiple robots. Physical implementations have used various information carriers in the role of pheromone, including projected visual images [4] and disappearing ink [5] detected by visual sensors, and have explored use of volatile chemicals in conjunction with chemical sensors [6]. Such systems could be used in situations where resources need to be found and retrieved in an unknown environment, as with raw materials near an autonomous extraplanetary base, or survivors in a disaster area.

In these systems, the environment is able to store and convey different kinds of information using a single carrier, based on the presence or absence of the signal, as well as its intensity. Relevant position and path information are directly embodied through the spatial distribution of the carrier. Reinforcement of the path by other successful foragers means that a stronger trail will typically mean a larger or more active resource supply. The fading of the carrier with time keeps the information represented by deposited pheromones up-to-date, and ensures that the swarm will not expend energy trying to exploit exhausted resource sites, without individual agents needing to take any explicit action.

III. Collective construction

Social insects use environmental cues to coordinate other activities as well. The term "stigmergy", which is frequently used in studies of natural and artificial swarm systems and refers to indirect coordination mediated by manipulation of a shared environment, was coined by a biologist studying nest construction by termites [7]. Termites manipulating building material are more likely to deposit new material in places where others have recently deposited other material, or where the atmospheric composition or temperature changes abruptly (as when repairing a break in the wall of a mound). The actions of these insects can be in response either to actions taken by other insects, or to environmental attributes less directly controlled by the swarm.

Such examples of construction performed by insects have inspired the design of systems for construction by artificial swarms of mobile robots. Some studies have addressed the "forward problem", by first specifying a set of actions and the conditions under which agents will take them, and then reporting on characteristics of the resulting structures [8]. Others have addressed the "inverse problem", with the explicit goal of generating a particular target structure, and then setting out to find a set of agent actions and conditions that is guaranteed to produce that structure [9]. Both approaches are relevant to the scientific question of how local rules give rise to global outcomes. The forward problem is more closely tied to the way insects build, producing some acceptable structure but not one whose details are predictable beforehand. The inverse problem is more in line with human goals in construction, reliably building a structure fully specified in advance.

Environmental information in this setting may include the configuration of building materials or presence of chemicals deposited directly by the builders [7], [9], other environmental elements (e.g., obstacles or light levels) not directly controlled by the builders [7], [10], and multiple kinds of building material [8], [11]. In artificial systems where the goal is to build a specific structure in a particular location, an especially useful kind of information to store in the environment, and one particularly well-suited to being stored there, is positional information, such as the location of a landmark encoded in a common coordinate system shared by all agents [9]–[11].

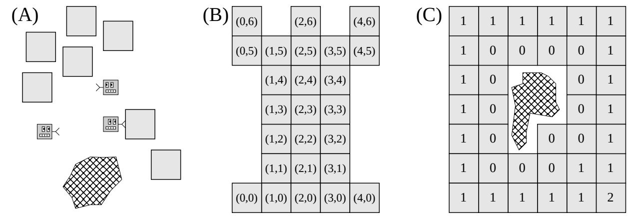

Fig. 1. (A) In collective construction, a set of robots uses supplied material to build a structure, potentially in the presence of obstacles. Storing spatial information in the building material can coordinate the robots' activities without requiring explicit communication. (B) When the desired structure is fully specified in advance, coordinates are a useful form of information to store in square building blocks. (C) If the desired structure is a function of the environment, storing other forms of information may be more useful. For instance, when the task is to build a wall of a certain thickness around an obstacle, a value associated with the distance from the obstacle is appropriate. Figure based on [10].

Such information can be encoded implicitly (e.g., by using only square blocks for building materials, which embody a coordinate system as they are assembled), or explicitly, for example by storing integer values in writable RFID tags deployed in the environment.

This last idea of using RFID tags to make the environment writable is a powerful one. RFID tags are inexpensive ($<$ \$0.50), small (mm to cm), robust (e.g., can operate at $>$ 400 °C), and capable of storing kilobytes of information rewritably and indefinitely without requiring a power source. This technology also provides a way to directly associate spatial information with physical locations. The next two sections describe further examples of how this capability can be useful.

IV. Simultaneous localization and mapping

In the problem of simultaneous localization and mapping (SLAM), one or more mobile robots need to build a map of an unknown environment as they move through and observe it. One of the classic SLAM problems is that of "closing the loop", i.e., determining whether a robot's location is one it has already visited or merely one that looks very similar. This common problem arises particularly in man-made interiors that often have many similar-looking corridors and doors laid out in a square grid. If particular locations in the environment are instrumented with uniquely-labeled RFID tags, or if robots are able to deploy tags themselves as they move, then each tag serves as a unique landmark and closing the loop is trivial. Similarly, in less structured environments, it can be very hard to establish reliable landmarks for position; deploying tags over time and space generates location information in the environment and solves this problem.

Writable RFID tags can store additional information to aid robots in performing their tasks. For instance, in an exploration task where multiple robots need to create a map of an unknown environment, robots should distribute their efforts in as non-overlapping a way as possible to minimize time and energy costs. If spatially distributed RFID tags are present, or if robots can deploy them, then each tag can store local information to

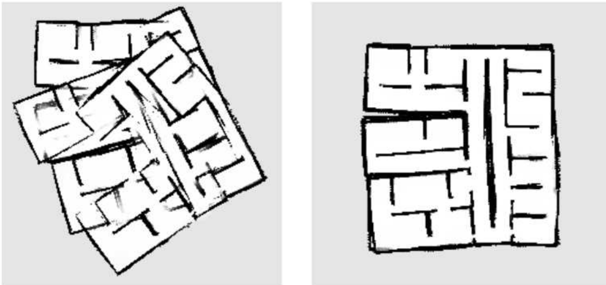

Fig. 2. Relying on robot odometry and laser range finder readings in an exploration task tends to result in numerous map misalignments (left). Deploying RFID tags to provide reliable landmarks can greatly improve the result (right). Figure reproduced from [12] (©2006 IEEE).

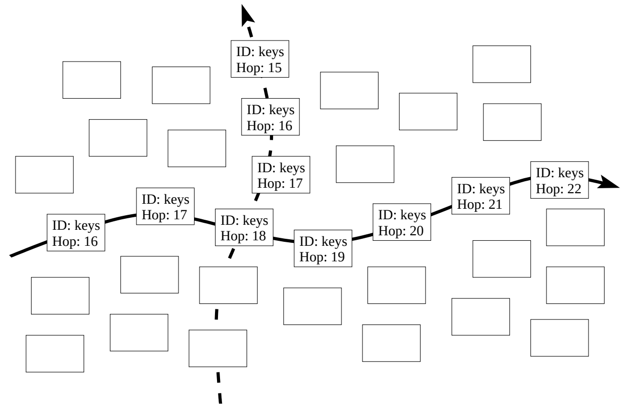

Fig. 3. An environment instrumented with RFID tags (rectangles) can store information about the movement of objects. An agent carrying an object of interest (e.g., keys) records its path (solid line) on tags as a pheromone trail, incrementing a hop counter as it travels. Another agent may later cross the trail (dashed line) and spread this information in another direction. If the object is misplaced and the trail can be found, an agent can follow the trail up the gradient to the object. Figure based on [14].

indicate which regions have already been visited by robots, and which are already targets of exploration [12]. This mechanism allows large numbers of mobile robots to coordinate their behavior in situations where explicit communication may not be feasible or reliable.

A similar principle could be used, for instance, by soldiers making their way into and out of enemy territory at night or under otherwise unfavorable conditions. Leaving an RFID-based trail, like Hansel and Gretel following their path of stones, could facilitate their movement in environments like indoor ones where GPS is not available, and without drawing the attention that a trail of active beacons could invite. If RFID tags become pervasive in human environments, as some foresee, then soldiers could make use of existing tags located in their new environment to encode signals helpful to them without even needing to bring their own.

V. Pheromone-based object tracking

There are many other settings where storing information in the environment can be helpful. In one framework, pervasive RFID tags act as a substrate on which the electronic equivalent of pheromones can be laid by humans or robots carrying RFID transceivers as they move around. The passive substrate can perform no computation and so these artificial pheromones can not fade on their own with time; however, writing timestamps along with the pheromone data allows later visitors to update the pheromone value based on how much it would have decayed in the interim.

These electronic pheromone trails can be used, for example, to record someone's movements after they put down their keys or eyeglasses, in order to help them find their way back to the object if it becomes "misplaced". Moreover, the pheromone value in this context can be used to reflect the distance from the object (rather than the strength of the trail as in the foraging context discussed above). The pheromone values in a region of tags then constitute a gradient that the user can follow back to the object, much like living cells migrate up gradients of immobilized chemical information in a process known as "haptotaxis" during development, wound healing and inflammation [13]. Other agents can spread pheromone values across the RFID array as they travel, increasing the range and usefulness of the field of values [14]. The environment then broadly contains information about the location of the object of interest, stored passively so that it can be retrieved as needed at a later time. Again, active long-range communication is not required for this type of implicit communication and coordination.

VI. Epithelial tissue

Another example of a natural system relevant to spatial computing in which the physical environment plays an often underappreciated role is in the control of tissue growth and form during development and maintenance of living tissues. The innumerable cellular components that make up developing embryos and adult tissues are often thought of as independent computing agents that follow programs encoded in their DNA, and coordinate their activities by chemical communication and other forms of cell-to-cell signaling. Less often considered is the role of the physical microenvironment, which can be equally important for control of tissue form and function.

Most research on biological regulation has focused on the role of soluble hormones and chemicals, or cell-cell adhesions, which can mediate cell-cell (agent-to-agent) communication and thereby control cell behavior. However, this picture is incomplete; the extracellular matrix (ECM) scaffolds that hold cells together within all living tissues are environmental elements that are deposited and modified by cells, and feed back to regulate cell growth and function during tissue development. For example, the ECM contains insoluble molecules that mediate cell anchorage, and the local density of these adhesive components can influence the direction of cell movement, as in the haptotactic process described above [13]. More interestingly, regional variations in ECM mechanical properties can direct cells to alter their behaviors (e.g., growth, death, differentiation, motility) locally and thereby generate distinct tissue patterns at a larger size scale through a process known as "morphogenesis". For example, during morphogenesis of the epithelial tissues that line the surfaces of our body and blood vessels, localized thinning of the ECM results in regional distortion of the ECM and adherent cells due to endogenous cell contraction. The cells that become stretched in these regions respond to growth stimuli by proliferating, whereas neighboring retracted cells remain quiescent; this cell division differential results in local budding or branching. The ECM thinning is the result of the action of enzymes produced by the cells. Thus, regional modification of the composition and structure of the common ECM scaffold, as well as local alterations of cell tension, may be primary mechanisms by which the entire population of cells controls its global form and function during tissue pattern formation [15].

Similarly, cancer is most typically thought of as caused by gene mutations that lead to uncontrolled cell division. However, deregulation of the normal developmental mechanism for local sensing of normal environmental cues described above can actually lead to disorganization of normal tissue form and promote cancer formation [16]. More specifically, altering ECM remodeling, structure and mechanics can transform normal epithelial cells and cause them to form into cancerous tissues. Conversely, some cancers can be induced to differentiate and cease proliferating by being combined with normal ECM or embryonic tissues [16], [17]. Thus, interactions with these passive extracellular elements play a crucial role in regulating both normal and pathological cell behavior. Although modular robots have been created that make use of physical interactions between multiple cellular agents [18], [19], this concept of using physical cues stored in a shared external scaffold for coordination and control of spatially distributed computing systems remains to be explored in the future.

A further way that passive structural elements in the ECM can influence cell behavior is through the use of "stormones". These are chemical signals embedded in the ECM so as to be inaccessible under normal circumstances, but under the appropriate conditions, they can be released with important effects on cell behavior. For instance, corneal cells synthesize an angiogenic growth factor and store it in the corneal ECM. Upon mechanical injury to the ECM, the growth factor is released, attracting the development of new blood capillaries that grow into this site from preexisting vessels located at a distance to supply the area with oxygen and nutrients necessary for tissue repair [20].

The use of stormones in living tissues suggests the potential utility of this mechanism in other natural and artificial systems. For instance, when their nest is breached, termites secrete a pheromone that is used as an alarm signal. To our knowledge, no such pheromone is known to be stored in the material of the nest itself. However, if such a pheromone were stored and released when the nest material was forcibly disturbed, it could allow a faster colony response, not relying on the presence of termites at that moment in the damaged area. We suggest that a search for such a mechanism in colonies of nest-building social insects might find it in use. The principle could likewise be useful as a damage-reporting mechanism in long-term human-made structures.

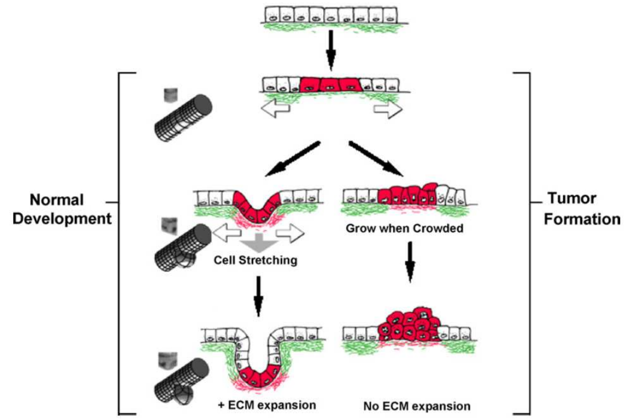

Fig. 4. Thinning and stretching of the extracellular matrix (ECM) leads to local cell division and budding (left). Cell division without ECM stretching can lead to cells piling up and tumor formation (right). Figure reproduced from [17].

VII. Discussion

The potential role of the environment as a key control element is important to keep in mind when studying or designing spatially distributed computing systems, or else crucial factors or straightforward solutions may be overlooked. For instance, attempts to fully understand ant foraging or cell behavior in living tissues would fall short if one considered only insect-to-insect encounters, or thought about cell behavior merely in terms of gene programs and chemical signaling. This is because interactions between these agents and their environment are also critical for system-level control. Similarly, determining location in an unknown environment is an extremely difficult task for mobile robots; however, the problem becomes trivial if local information can be stored in the environment or if reliable landmarks can otherwise be created. We therefore suggest that it is critical to broaden the view of spatially distributed computing systems to encompass the spatial environment that they inhabit.

Not all spatial computing systems will necessarily lend themselves to use of the environment. In some cases, the computing devices may be the sole elements present (as in idealized studies of sensor networks or amorphous computers). In others, the system may be designed such that external elements can only interfere with its successful operation (as in certain self-reconfigurable robotic systems). However, biological systems extensively modify and respond to the environment in addition to inter-agent communication, and many artificial systems have demonstrated the power of environmental coordination. Making use of this spatial information can provide a powerful mechanism to coordinate and control higher-order behavior of the whole collective.

The examples described above suggest an axis along which environmental elements can be characterized in terms of their information storage and processing capabilities. We outline these capabilities in order of increasing complexity:

1) Presence/absence of an indicator (e.g., local configuration of existing building material in collective construction); each location or environmental element stores or embodies a binary value.
2) Unique static label (e.g., RFID tags deployed to identify locations for loop-closing in SLAM); each element encodes a unique value, which need not change as the system operates.
3) Amount/degree of an indicator (e.g., pheromone values in foraging or object tracking systems, mechanical compliance of the ECM); each element stores a dynamic value, either discrete or continuous, potentially with some maximum range or limited resolution.
4) More general memory storage (e.g., coordinates stored in building blocks, descriptors and timestamps in virtual pheromones for object tracking); each element can encode arbitrary data for the benefit of the active agents, potentially with some specified memory limitations.
5) Active information processing (e.g., chemical pheromones that diffuse and fade, "communicating" building blocks [9], [11]); elements transform the information they are given in specific ways, potentially interacting with nearby elements to do so.

Clearly it is possible within the bounds of this classification scheme to approach the limits of what is best thought of as constituting the "environment". For instance, it may be more useful to think of environmental elements that perform active information processing as a second spatial computing system interacting with the first. Nevertheless, we think that the practice of considering the physical environment as a potentially useful resource for coordination and control of spatially distributed computing systems is worth pursuing. This biologically-inspired approach can promote appropriate division of labor in engineered systems [9], and highlight processes that might otherwise be overlooked in natural ones [15]. Beyond this general principle, we hope that the examples and categorization discussed here, and their illustrations of what different materials and classes are capable of and how they may be used, will serve as the beginning of a taxonomy useful for future system design and understanding.

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