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Swarm Robotics: From Sources of Inspiration to Domains of Application

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Oğul Robotbilim: Esin Kaynaklarından Uygulama Alanlarına

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Öz

Oğul robotbilim, esin kaynağını sosyal böceklerden alıp büyük sayıda ve göreceli olarak basit robot sistemlerinin koordinasyonuna yönelik yeni bir yaklaşımdır. Bu makale, yeni ortaya çıkan bu yaklaşımı tanımlamaya yönelik olarak; 1) sosyal böceklerin sistem seviyesinde çalışmasında gözlenen ve oğul robot sistemleri için istenilir olan özellikleri açıklamakta, 2) oğul robotbilim için bir tanım önererek, bu yaklaşımdaki çalışmaları diğer çoklu-robot çalışmalarından ayırdetmede kullanılacak bir dizi kriter önermekte, ve 3) oğul robot sistemlerine esin kaynağı olabilecek bazı çalışmaları özetleyip, oğul robot sistemlerinin uygun olabileceği bazı uygulama alanlarını işaret etmektedir.

Abstract

Swarm robotics is a novel approach to the coordination of large numbers of relatively simple robots which takes its inspiration from social insects. This paper proposes a definition to this newly emerging approach by 1) describing the desirable properties of swarm robotic systems, as observed in the system-level functioning of social insects, 2) proposing a definition for the term swarm robotics, and putting forward a set of criteria that can be used to distinguish swarm robotics research from other multi-robot studies, 3) providing a review of some studies which can act as sources of inspiration, and a list of promising domains for the utilization of swarm robotic systems.

1 Introduction

Swarm robotics is a novel approach to the coordination of large numbers of robots. It is inspired from the observation of social insects —ants, termites, wasps and bees— which stand as fascinating examples of how a large number of simple individuals can interact to create collectively intelligent systems. Social insects are known to coordinate their actions to accomplish tasks that are beyond the capabilities of a single individual: termites build large and complex mounds, army ants organize impressive foraging raids, ants can collectively carry large preys. Such coordination capabilities are still beyond the reach of current multi-robot systems.

2 Motivations for swarm robotics

Studies[12] have revealed that there exists no centralized coordination mechanisms behind the synchronized operation of social insects, yet their system-level functioning is robust, flexible and scalable. Such properties are acknowledged to be desirable for also multi-robot systems, and can be stated as motivations for the swarm robotics approach:

- **Robustness** requires that the swarm robotic system should be able to continue to operate, although at a lower performance, despite failures in the individuals, or disturbances in the environment. As anyone who tried to extinguish an ant raid into his kitchen would agree, social insects are extremely difficult to get rid of. This robustness can be attributed to several factors; First, redundancy in the system; that is, any loss or malfunction of an individual can be compensated by another one. This makes the individuals dispensible. Second, decentralized coordination; that is, destroying a certain part of the system will not deter the system's operation. Coordination is an emergent property of the whole system. Third, simplicity of the individuals; that is, in comparison to a single complex system that could perform the same task, in a swarm robotic system, individuals would be simpler, making them less prone to failures. Fourth, multiplicity of sensing; that is, distributed sensing by large numbers of individuals can increase the total signal-to-noise ratio of the system.

- **Flexibility** requires the swarm robotic system to have the ability to generate modularized solutions to different tasks. As nicely demonstrated by ants, in ant colonies individuals take part in tasks of very different nature such as foraging, prey retrieval and chain formation. During the foraging task, ants act independently searching for food in the environment; their search is partially coordinated by the pheromones laid in the environment. The prey retrieval task requires the ants to generate a force much larger than that of a single individual to drag a prey to the nest. When a large prey is discovered, each ant grip the prey with its mandible and pull it in different directions. The seemingly random pulls of ants are observed to be coordinated through the force integrated over the prey. In the chain formation task, ants form a physical chain-like structure that can extend beyond the reach of a single ant and exert large forces pulling together leaves. During the task, ants use their body as a medium of communication where ants in the chain act motionless with each ant gripping/holding the leg of other ants in the chain. In this task, coordination is achieved through the bodies of the ants. Swarm robotic systems should also have the flexibility to offer solutions to the tasks at hand by utilizing different coordination strategies in response to the changes in the environment.

- **Scalability** requires that a swarm robotic system should be able to operate under a wide range of group sizes. That is, the coordination mechanisms that ensure the operation of the swarm should be relatively undisturbed by changes in the group sizes.

Although we have presented the inspiration behind the swarm robotics approach, and described its envisioned properties as observed from natural systems, these by themselves are not sufficient to define the approach. In the next section, we propose a definition of the term, followed by a set of criteria to support the definition given.

3 Swarm robotics

The term *swarm intelligence* was first coined by Gerardo Beni[10] as a "buzz word" to denote a class of cellular robotic systems (see[9] for a brief history). However, the term was embraced more by the social insect studies and by the optimization studies that used the social insect metaphor, losing much of its original robotics context[11]. During recent years, the term swarm robotics emerged as the application of swarm intelligence to multi-robot systems, with emphases on physical embodiment of the entities and realistic interactions among the entities and between the entities and the environment. In a sense, the term swarm robotics took the heir of swarm intelligence which moved on to cover a broader meaning.

Although, like every other newly coined term, swarm robotics will have a life of its own to claim its meaning, our observations indicate that such new terms run the risk of turning into buzz words that tend to be attached to existing approaches with little thought over whether it really fits or not. Such misuses, in time, can drift the term in every direction blurring the very point that made it novel. In an attempt to prevent this, we will propose a definition and a set of distinguishing criteria for the swarm robotics approach.

As our starting point, we propose the following definition for the term swarm robotics: *Swarm robotics is the study of how large number of relatively simple physically embodied agents can be designed such that a desired collective behavior emerges from the local interactions among agents and between the agents and the environment.*

This definition by itself, however, is not sufficient to properly describe this newly emerging term. Within the multi-robot research only (see [18] and [13] for two rather out-dated surveys of the field), there already is a plethora of terms labeling different flavors of multi-robot research such as "collective robotics"[19, 20], "distributed robotics"[3], "robot colonies"[4], with often vague and overlapping meanings. Therefore, we would like to put forward a set of criteria for distinguishing swarm robotics research.

3.1 Autonomous robots

As much as it seems obvious, we believe that the requirement that the individuals that make up the swarm robotic system be autonomous robots needs to be explicitly stated. That is, the individuals should have a physical embodiment in the world, be situated, can physically interact with the world and be autonomous. Sensor networks[2] that consist of distributed sensing elements, but with no physical actuation abilities, should not be considered as swarm robotic systems. Yet we believe that the studies on sensor networks are highly relevant for swarm robotics.

The metamorphic robotic systems[14, 26], in which units adhere to each other and can only move over each other by forming and disconnecting connections with other units can also be considered as swarm robotic systems as long as there exist no centralized planning and control centers.

3.2 Large number of robots

The study should be relevant for the coordination of a "swarm of robots". Therefore, studies that are applicable to the control of only a small number of robots and do not aim for scalability, fall outside swarm robotics. Although putting a number as a lower bound of group size is difficult to justify, and most would accept group sizes of 10-20 as "swarms". Despite the lowering cost of robots, maintainance and experimentation with large groups of robots will remain as a main obstacle. Therefore the issue of relevancy is mentioned to express that the field should be open to studies that are carried out with smaller group sizes, but with the vision/promise of scalability in sight.

3.3 Few homogenous groups of robots

The robotic system being studied should consist of relatively few homogeneous groups of robots, and the number of robots in each group should be large. That is, studies that are concerned with highly heterogeneous robot groups, no matter how large the group is, are considered to be less "swarm robotic". For instance, studies on robosoccer teams mostly fall outside of swarm robotics since these teams typically consist of individuals whose different "roles" are assigned to them by an external agent prior to the operation of the team and hence they are highly heteregenous.

We agree that, the issue of homogeneity in a group of robots is not a trivial one. In [5] Balch proposed a metric, called the hierarchical social entropy, which can be used for this purpose. Yet, it is difficult to determine whether two individuals belong to the same group or not using a simple evaluation run in the *evaluation chamber* as proposed in[5]. This is due to two reasons: 1) the nonlinear inter-robot interactions will have a large affect on the behavior of the robots, and 2) probabilistic behaviors can make it impossible to obtain exact similar evaluation runs under exactly the same conditions.

3.4 Relatively incapable or inefficient robots

The robots being used in the study should be *relatively* incapable or inefficient on their own with respect to the task at hand. That is, either 1) the robots should have difficulties in carying out the task on their own, and the cooperation of a group of robots should be essential, or 2) the deployment of a group of robots should improve the performance/robustness of the handling of the task. Collective retrieval of a large prey by ants is a good example to the first case where retrieval by a single ant would be impossible. Collective foraging of ants using pheromones laid on the ground for stigmergic communication create foraging patterns which are believed to improve their foraging performance[12]. Using a group of simple mobile robots, Sugawara et al[23] showed that signalling the discovery of an object in environments where objects are non-uniformly distributed can yield super-linear increases in the performance of the swarm.

It is important to note that this criterion does not impose any restrictions on the hardware and software complexity of the robots. The incapability and inefficiency of individual robots should not be taken in absolute terms, rather they should be seen relative to the task and be considered as a justification for the simplicity of robots.

3.5 Robots with local sensing and communication capabilities

The robots being used in the study should only have local and limited sensing and communication abilities. This constraint ensures that the coordination between the robots is distributed. In fact, the use of global communication channels within the robot group is likely to result in unscalable coordination mechanisms and would therefore act against the first criterion mentioned above. However, note that the global communication channels, which can be used as a means to download a common program onto the swarm, is acceptable, as long as it is not used for coordination among the robots.

We would like to warn the reader that the definition and the list criteria humbly expresses our current understanding of this newly emerging approach, as partially shaped by discussions held during the workshop. The reader should keep in mind that these criteria are not meant to be used as a checklist for determining whether a particular study is a swarm robotics study or not. Instead, they should be used as yardsticks for measuring the degree to which the term "swarm robotic" might apply. We hope that these views will act as a seed[1] for further discussion which will promote a better definition of "swarm robotics".

[1]The discussion presented here extends from the views first put forward by Dorigo and Şahin in [16].

4 Sources of inspiration

There are many research fields that can act as sources of inspiration for swarm robotics. First and foremost among them is the study of self-organization, which is defined[12] as "a process in which pattern at the global level of a system emerges solely from numerous interactions among the lower-level components of the system". In this sense, swarm robotics can be considered as the engineering and utilization of self-organization in physically embodied mobile swarms.

Studies of self-organization in biological systems show that an interplay of positive and negative feedback of interactions among the individuals is essential for such phenomena. In these systems, the positive feedback is typically generated through autocatalytic behaviors. The snowballing effect triggered by the positive feedback cycle is counterbalanced by a negative feedback mechanism, which typically stems from a depletion of physical resources in the system or the environment.

Studies that attempt to uncover the principles behind the emergence of self-organization in biological systems, often develop models that are built with simplified interactions in the world and abstract behavioral mechanisms in individuals. Self-organization models of social insects and animals have already been used as inspiration sources for many swarm robotics studies.

Below, we would like to draw attention to three other lines of research, which we believe, contain ideas that can act as inspiration sources. In our reviews, we tried to emphasize the ideas that, we consider, most relevant and inspiring for swarm robotics research.

4.1 Unicellular organisms

Some species of unicellular organisms, such as bacteria, myxobacteria, amoeba, are observed to display interesting examples of coordination. These organisms, which act independent of each other under favorable conditions (plenty of food, no antibiotics, etc.), are observed to display coordinated behaviors when times get hard.

4.1.1 Aggregation of amoeba into slime mold

Aggregation is a highly observed phonemena in various life forms since it constitutes a pre-condition of most collective behaviors. One well known example of aggregation is observed during the formation of the slime mold by the *D. discoideum* from cellular *Dictyostelium* amoeba [12]. When the food is abundant in the environment, these amoeba feed and multiply with no signs of coordination among different individuals. When the food supply is depleted, however, the amoeba begins to aggregate forming complex spatial patterns. The aggregation process creates a slug, a multicellular organism which can move on a surface for some time, and then sporulate.

Studies have shown that the aggregation is governed by cAMP, a chemoattractant that is produced and released into the extracellular environment by the starving amoeba. It is shown that amoeba have two modes of cAMP secretion: oscillatory and relay. In the oscillatory mode, starving amoeba releases cAMP with a period of 5-10 minutes. In the relay mode, that is when the amoeba is hit by a cAMP pulse, the amoeba responds by a producing a larger cAMP pulse. The positive feedback of cAMP production cycle is bounded by the desensitization of cAMP receptors in high cAMP concentrations. This mechanism is shown[12] to generate spiral cAMP waves that propagate in one direction. The cAMP waves guide the cells towards the center of the spiral, which once begin to adhere to each other, create clumps that are difficult to disperse.

The amazing aspect of this aggregation process is its size; typically 10,000-100,000 cells aggregate to form the slime mold. Experiments on developing controllers for aggregation of mobile robots, which use sound or light for long range signalling, indicate that even aggregation of individuals on the order of 10's is very difficult [17]. The gap between the scales of aggregation suggests that stigmergic communication (which occurs through cAMP concentration in the extracellular environment of amoeba) is very important. Long range signalling modalities, such as sound and light, that are typical on mobile robots are not persistent in the environment as chemicals making them unusable for such stigmergic coordination. Two possible strategies to use stigmergy in swarm robotic systems exist. First, one can use embedded intelligent markers in the environment which can store stigmergic information and interact with each other to simulate physical diffusion like signal spreading. Gnats[6] or smart materials like those envisioned by the amorphous computing paradigm [1] can used for this purpose. Second, in a large swarm, some of the individuals can make themselves immobile and act as a stigmergic medium to guide the rest of the swarm. Although similar ideas were used in [22, 21] for route discovery and following, their use are rather limited and the idea needs to be exploited for other tasks as well.

4.1.2 Quorum sensing and communication in bacteria

Recent studies of bacteria[7] started to reveal intricate communication mechanisms within bacteria colonies. Some species of bacteria are known to use quorum sensing to synchronize their actions: *Vibrio fischeri* produces light when its population reach a critical size, *Vibrio cholarae* delays the production of virulance factor in their host bodies until they reach a certain mass, possibly to ensure a successful infection by reducing the chance of immune system alert. Recent studies indicated that quorum sensing is done by the detection and production of extracellular chemicals called autoinducers that modulate gene expression. The discovery of different autoinducers and quorum sensing mechanisms in bacteria suggests that interactions between them can play an important role for the formation of complex structural organizations composed of multiple bacteria species.

Quorum sensing is a fundamental problem for swarm robotics that is yet to be faced. Therefore coordination mechanisms revealed in bacteria are very relevant. Although we would admit that the current state of the studies reviewed above, does not provide sufficient detail about these mechanisms yet, it is likely to do so in the very near future and therefore worth to keep an eye.

4.1.3 Information exchange in bacteria

It is observed[8] that "bacterial colonies can be far more resistant to antibiotics than the same bacteria living in suspension". It is thought that bacteria living in colonies form a genomic web and the enhanced robustness is due to the communication capabilities of bacteria through chemical signalling or the transfer of genetic material. The communication capabilities can be classified into two different categories: inducive and informative. In inducive communication, the (chemical) signal triggers a certain action within the cell. In informative communication, however, the message received is interpreted by the cell and the response is based on the current state of the cell and its history.

In real life, it is highly likely that some individuals of swarm robotic systems will discover certain hazards the hard way, through being destroyed by these hazards. Utilization of an information exchange mechanisms, inspired from bacterial communication, that can pass last-minute signals or codes to other individuals has the potential of improving the robustness of the swarm robotic systems in unknown environments.

4.2 Amorphous Computing

Amorphous computing, proposed by Abelson[1], sets its challenge as "How can prespecified, coherent behavior be engineered from the cooperation of vast numbers of unreliable parts interconnected in unknown, and time-varying ways?" This line of research considers "a system of irregularly placed, asynchronous, locally interacting computing elements" as a medium and aims to develop programming paradigms for translating a desired global pattern onto a finite set of rules to be executed by the elements. Their approach takes its inspiration from the morphogenetic processes in biological systems, such as tissue growth. In [15], Coore developed a programming language, called the growing-point language, which can be used to grow patterns in an amorphous medium through directed wave (message) propagation. Although there is no limitation on the mobility of the elements, work carried out so far has focused on immobile elements. Despite this, the programming paradigms developed in this line of research, we believe, are relevant for swarm robotics research.

4.3 Self-assembly of materials

Self-assembly, defined as "the autonomous organization of components into patterns or structures without [external] intervention" [25], is of interest at different scales; Molecular self-assembly is useful for fabricating materials with regular structures (such as molecular and liquid crystals), nanoscale self-assembly stands as a promising method for building large numbers of micro electro-mechanical systems, meso- to macroscopic (objects with dimensions from microns to centimeters) self-assembly can aid robotic assembly process.

In [24], Whitesides and Boncheva argue that for successful molecular self-assembly the following characteristics be present; 1) the components should be designed for the desired structure, 2) the components should be mobile with respect to each other, 3) there exists an equilibrium of attractive and repulsive forces at the desired configurations of the components, 4) associations between the molecules should be reversible, allowing molecules to adjust their positions with respect to each other, 5) the environment should guide the interactions in the desired way.

Browsing through self-assembly literature, we discovered two other interesting ideas for swarm robotics research. One idea is the use of templates. It can scaffold the process reducing the defects in self-assembly. Another is the use of catalytic agents. Both ideas have the potential to improve the pattern formation performance in large swarm robotic systems and worth to be explored.

5 Domains of Application

Mass production of robots is essential for the deployment of swarm robotic systems. Advances in mechatronics technology have already started to shrink the size and costs of traditional autonomous robots. MEMS (Micro-Electro-Mechanical System) technology has been making impressive progress on the integration of mechanical, sensor, actuator and electronics components on silicon substrate opening the way to fully-autonomous micro-robots. As the mass produced robots, at macro, micro and nano levels, become available their cost will be relatively much cheaper (with respect to other single-robot solutions) making the individuals dispensible.

Below, we present a number of task domains where the swarm robotics would be applicable. We emphasize the properties of the tasks that make them suitable for swarm robotic systems, and provide a number of real-world problems as examples.

5.1 Tasks that cover a region

Swarm robotic systems are distributed sytems and would be well-suited for tasks that are concerned with the state of a space. Environmental monitoring (or tracking the well-ness) of a lake, would constitute a good domain of application. The distributed sensing ability of swarm robotic system can provide surveillance for immediate detection of hazardous events, such as the accidental leakage of a chemical. In dealing with this, a swarm robotic system would have two major advantages of sensor networks, which can also be considered as immobilized swarm robotic systems. First, in such a case, a swarm robotic system has the ability to “focus” on the location of problem by mobilizing its members towards the source of the problem. Such ability would allow the swarm to better localize and identify the nature of the problem. Second, the swarm can self-assemble forming a patch that would block the leakage.

5.2 Tasks that are too dangerous

Individuals that create a swarm robotic system are dispensible making the system suitable for domains that contain dangerous tasks. For instance, clearing a corridor on a mining field can be cheaply accomplished by a swarm of robots. Unlike a single (more complex and expensive) “robotic de-miner” designed for the same task, the members of the swarm can afford being “suicidal” for carrying out their task by marching through the field. We would also argue that, a corridor that is marched by a swarm of robots would be safer than the one that is checked by the single “robotic de-miner” since the swarm robotics approach would physically walk over the mines, simulating the walk of the soldiers.

5.3 Tasks that scale-up or scale-down in time

Swarm robotic systems have the power to scale-up or scale-down with the task at hand. For instance, the scale of an oil leakage, from a sunk ship, can increase dramatically as the tanks of the ship breaks down. A swarm robotic system which self-assembled to contain the initial spillage in a bounded area, can be scaled up by the “pouring” more robots into the area.

5.4 Tasks that require redundancy

The robustness of swarm robotic systems come from the implicit redundancy in the swarm. This redundancy allows the swarm robotic system to degrade peacefully making the system less prone to catastrophic failures. For instance, swarm robotic systems can create dynamic communication networks in the battlefield. Such networks can enjoy the robustness achieved through the reconfiguration of the communication nodes when some of the nodes are hit by enemy fire.

6 Conclusions

In this paper we tried to define the newly emerging field of swarm robotics as a new aproach to the control and coordination of multi-robot systems. We stated the inspirations behind this approach, the desirable properties, and the requirements to clarify the defining characteristics of this approach in relation to other existing studies. However, the reader should note that like any other approach, this approach should not be seen to be applied in its pure "crystal" form to real problems. These clarifications are provided with the hope that it will guide the researchers to reveal the mechanisms behind, which can then be mixed with other approaches.

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