Swarms of Unmanned Vehicles for Area-Scan: Conceptual and Practical Control Aspects

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ABSTRACT

Through several Research Projects our team has acquired some experiences, related to the control of groups of mobile vehicles. We investigated how to develop distributed control, according with the swarm concept that each unit takes own decisions. Based on potential fields, we got swarm anonymous formations of different types. Other research activities were oriented to create ant colonies, with a mixed population of explorers and foragers. The experimental research is done with simulations and experiments using small ground robots and moderate size unmanned ships. Our interest focuses on scan-area for mine detection. A main experience is that the local control of each swarm member could be not so simple, since different combinations of relative location circumstances happen. Simulated experiments with ants show that the proportion of explorers and foragers should adapt to the current uncertainty.

1.0 INTRODUCTION

Through several Research Projects, with support from the European Community and the European Defence Agency (EDA), we investigated how to develop decentralized control, according with the swarm concept that each unit takes own decisions.

In each of the sections of this text, we included references that give extended details on the aspects we wish to discuss.

The scientific interest on swarms started in a biological context. The behavior of animal groups became a subject of study. It also entered into the focus of other research fields. For example, one of the key papers on flocks, herds and schools was presented in a Conference of Computer Graphics [1].

During the years when the research started to consider teams of mobile robots, a seminal book on the behavior of animal groups appeared [2] (MIT Press). In this book, several key observations were done. For instance that formations of birds work in silence, there is no need of message exchanging. Furthermore, the vertex of a V formation is taken by one after one bird, so the leader is constantly changing. And the geometry of the impressive V formation emerges from basic local behaviors of each bird.

A decade before the book [2], the subsumption architecture proposed by [3] paved the way for the development of mobile robots, based on a set of simple behaviors. One year after [2], [4] proposed a behavior-based formation control for multi-robot teams. A lot of related research started. Let us mention the article [5] on coordination of groups of mobile robots using nearest neighbor rules. Another article of interest is [6] on algorithms and theory concerning flocking of multi-agent dynamic systems. Some of the reasons for considering dynamic systems are problems with oscillations and instability. A familiar example of this is dense traffic of cars. A simple local rule for drivers is to follow the car before you. This turns out to be like a virtual spring between cars. It happens that a chain of two springs tend to oscillate, and more springs become still worse. When a car unexpectedly slows down, a crash may occur several cars behind. Formation chains require a delicate local control tuning. In the case of airplanes, it is better not all to flight at the same altitude (bird V formations apply this trick). Control engineers should consider 3D scenarios when dealing with a group of AUVs or UUVs.

We will insist on simulation testing before real experiments. Simulations are based on mathematical models. A concise review of mathematical models of robotic swarms is provided by [7]. For certain applications it would be natural to adhere to a stochastic or Bayesian framework.

In the next sections we would consider peculiar aspects of swarms.

2.0 DECENTRALIZATION

One of the usual characteristics of swarms is that they are decentralized systems [8]. Let us comment this aspect. Here we invoke our experience with a European Research Project called Smartfuel. The target was to demonstrate a decentralized networked system with smart components for aircraft fuel system management. These components were valves, pumps, sensors, with embedded electronics, [9].

A first point to remark is that a networked system can perfectly be a centralized system, in the sense that decisions are taken by a central node, and then communicated to the rest of the system. Having a lot of communication among members of a team does not mean that the system is decentralized. Perhaps it could be said that the system is distributed, in a geographical sense or a task assignment sense, but decentralization refers to who is taking the decisions.

In the case of Smartfuel, each component was able to take own decisions based on local automata. For instance, the valve A opens if the system is in refueling mode and the tank is not full. There is state vector shared by all components through the network. The valve A uses this vector to know when the conditions to open appear. When the valve opens, it informs to the state vector that it is now open.

In more abstract terms, one would say that the members of the Smartfuel team have roles corresponding to their abilities, that they take local decisions, and that as a result the system has an adequate global behavior. The fuel system has a set of functional modes, or, in other words, a set of different global behaviors. Furthermore, the system is reconfigurable, having alternative ways for performing the desired functions (using structural redundancy). These observations also correspond to swarms.

The decentralized control of multi-robot teams has been extensively investigated. A representative article on this topic is [10]. A categorization and complexity analysis has been done by [11].

In a very readable article, [12] comments how the term 'swarm' was introduced. It was a better, and more attractive way to refer to cellular robots (obviously related to cellular automata). Actually we employed cellular automata to obtain initial solutions during our research on Ant Colony applications for vehicle control [13]. We observed that simple rules identically replicated on each of the automata, lead to complex global behaviors along an evolution. This emergence phenomenon is a typical characteristic of swarms.

Stephen Wolfram identified four classes of cellular automata:

- Class 1: after a stable and homogeneous evolution, the system converges to a single state.
- Class 2: the evolution converges to a state pattern, a trajectory, which is stable and periodic.
- Class 3: there is an unstable evolution, which does not converge to any pattern (a chaotic system).
- Class 4: the evolution converges to complex behavior where order and chaos coexist. There would be ordered regions, with local patterns, and other disordered regions.

Since the kind of evolution may depend on parameters of the local rules, it is important to simulate the result of local control specifications.

In the doctoral thesis [14], the use of cellular automata is proposed for the control of large robot formations. An example of current research on cellular automata and Ant Colonies for path planning of cooperative robot teams is [15]. An interesting critical review of S. Wolfram concepts is [16].

3.0 MULTI-ROBOT TEAMS

When dealing with groups of mobile robots, it is convenient to take into account different dimensions of order, like for instance space, time, roles, etc. We would like to fix some terms.

Given a target there is a question: what should be done. This is followed by who must do what (supposing several people). In general we would need *cooperation*. Imagine a chirurgical intervention done by a team of doctors, skilled nurses, anesthetist, etc. Each one has a role. In certain circumstances it would be possible to have a dynamic re-assignment (reconfiguration).

Now, let us observe what happens in a drift boat with several rowers. They must work in *synchronicity*, which is *temporal coordination*. The case of keeping a formation, a geometry (like migratory birds), is an example of *spatial coordination*.

A more extensive typological analysis of multi-robot work can be found in [17, 18].

In mobile robotics and other fields, a frequently used term is 'situated agent'. It could mean that the agent uses GPS, or perhaps it only knows its relative position with respect to some other objects.

Formations of men or robots offer easy motion control as a single entity. It is not so for dispersed groups, with probably no leader. Interestingly, the article [19] on animal groups' behavior says that among many individuals there would be some that have pertinent information on a food source or a migration route. Using a simple model it was shown that the larger the group the smaller the proportion of informed individuals needed to guide the group.

We did some research on anonymous formations [20, 21]. The robots have no ID. A blending of several potential fields was proposed. One of these fields corresponds to the formation shape (circle, triangle, etc.). The other potentials correspond to attraction to a target, obstacle avoidance, and robot-robot interaction.

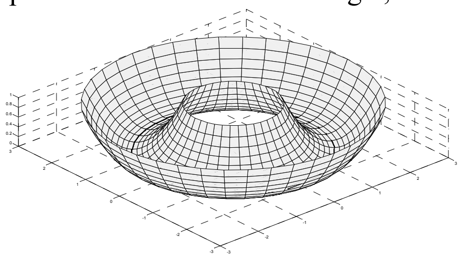

Figure 1: Formation shape potential for circular formation

The path to the target is discovered by the formation, which does not follow a leader; instead the motion of the group is a result of the motion of each member. We did a series of experiments with mobile robots to demonstrate the aggregation of the robots in a formation pattern. It should be said that the local rules of each robot must consider several ways to enter into the formation (ahead or behind other robot) while avoiding obstacles. Transitions between different formation patterns were also demonstrated. The experiments were used as a basis for the development of a simulation environment for larger experiments.

Next figure shows a simulated experiment with the formation avoiding some obstacles.

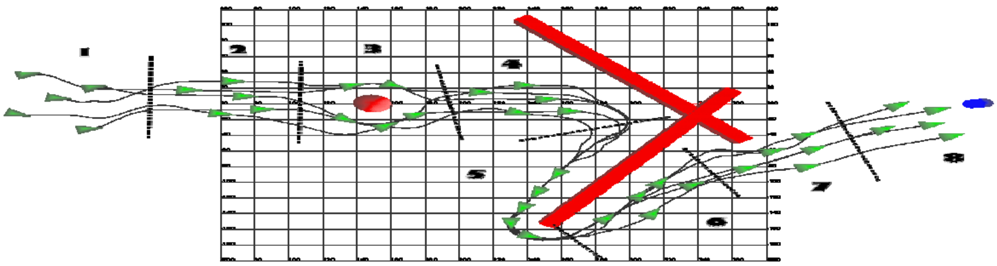

Figure 2: The anonymous formation avoids obstacles during its motion

We have particular interest on groups of autonomous boats (see [22] for concepts related to autonomy). Our first experimental activities considered a follow-the-leader approach both for in-line or front formations. A virtual leader was initially chosen, but practical difficulties arise related to the speed of the leader. When turning, the members of a front formation should have different speeds, the exterior member should speed up and may reach a maximum speed limit, loosing track of the virtual leader. It is better to take a member as real leader, and change this role according with turning left or right. Actually, in the end we changed the approach to a combination of path following and leadership. By means of an automatic planning method, we obtain an appropriate formation path for the operation at hand. The path can be compactly specified. Each member of the formation gets a copy of the path description. Each member is assigned a lateral distance to the path. The leader moves with a specified speed. The other members keep a specified distance to the leader along the path. Next figure illustrates the concept.

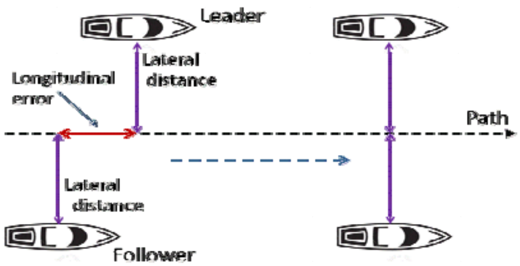

Figure 3: The boat formation combines path and real leader following

With proper modifications, the idea of a group path and keeping mutual distances (with some flexibility) could be applied to swarms.
From time ago we are developing an automatic oil spill confinement system. The proposal is to use two autonomous ships (USVs) for towing a boom. We applied the formation control just described, did experimental testing and…found a problem: the two ships rapidly evolve to a tug of war situation [23]. What happens is that physical interaction of vehicles, through the boom, presents a new control design scenario. A specific control law had to be added. The lesson for commercial USVs users is that these are conceived for individual work, not coupled with other vehicles. If one wants to use USVs for applications with physical interaction, a new software layer or component should be added to the on-board control. Next figure shows one of our autonomous boats being used for scan area and for towing.

Figure 3: One of our autonomous boats we use for experimental work

There are illustrative studies that include physical interaction, like [24] on the collective transportation of objects by a swarm; [25] on cooperation of swarm-bots, with examples of self-assembling, and collective object pushing; and [26] on self-assembly of a swarm of boats into floating structures.

4.0 SCAN-AREA

During military exercises on the sea using multiple UUVs and USVs from different producers, it is not easy to establish a cooperative work. One of the reasons for that is lack of compatibility. We are participating in an EDA Research Project called NECSAVE, which aims to establish networked systems of several types of autonomous vehicles, overcoming compatibility problems. A NECSAVE software adapter can be used to recruit any vehicle for the multi-vehicle team.
One of the scenarios considered for sea trials is area scan for the detection of mines. In the case of UUVs, the zone of interest is divided into 3D boxes. Possible failures of vehicles are considered, in which case other vehicles take care of pending boxes to be scanned. This situation is handled with an optimization algorithm related to the Travelling Salesman Problem (TSP). Our participation in this Project is the main reason for our interest on area scan with USVs. The Project considers also swarms. Next figure shows the GPS traces of a scan area experiment where the ship decides to divide the scan into two areas.

Figure 3: GPS traces of a scan area experiment with the autonomous boats

When speaking of swarms, a basic intuition is that they involve many individuals. It is not easy to devise a swarm of hundreds of mobile robots, so most published studies rely on simulations. Of course, there is a third way: to study animal swarms. Extending this alternative, it becomes fruitful to study human crowds [27, 28].
Therefore, let us learn from people. The natural scan area procedure when there is a plane crash on the sea, and survivors must be urgently found, is based on spiral paths (or modified versions in function of current and wind). When it is not urgent, but an exhaustive exploration of a terrain is needed, people organize as a dense front formation. In the case of locating submerged mines, a lawn mower procedure is the standard. And after an earthquake, people gather as several unstructured groups, around places where perhaps survivors can be found. At first sight one can discern two broad types of methods: systematic, or stochastic.
The abundant literature on the use of swarms for area scan confirms our initial observations. Let us try to summarize illustrative aspects of this research.
A first concern is energy efficient exploration paths. For one ground mobile robot, [29] concludes that for small areas straight scan lines are better, while for larger areas spirals are preferable because the robot can continuously move without stopping and turning.
The searching of certain targets with an UAV is treated in [30]. In the case of survivors, the UAV follows a series of circles with centers on a spiral, in order to use its camera. Another scenario considers rugged mountain terrain with canyons, and uses an A* path planner. The case of the detection of moving targets with and UAV is treated by [31].
It would be recommended to examine the Thesis [32] on path planning for UUVs. It includes opportune reviews of scan methods, considering also 3D scenarios; and also multi-robot contexts.
The term ‘coverage’ has several meanings. For robots doing vacuum cleaning, harvesting, painting, lawn mowing, etc., it would mean that once completed the operation there are no untouched patches. This is the sense in [33], which uses rectangular tiling and SLAM (the robot incrementally builds a map). Likewise, [34] uses cell decomposition, and a spanning-tree ant-like algorithm for indoor exploration. It should be

said that exploration of buildings is an important challenge.

When using mobile phones one sees if there is coverage. This is another sense of the term 'coverage' that implies a number of nodes placed on certain strategically good locations. Obviously, this scenario calls for multi-robot or swarm application. A kind o diffusion-limited process is proposed in [35], so the ground robots (belonging to a networked swarm) wander randomly until finding a good spot. A method for obtaining 2D sensor networks with robot swarms not having GPS is proposed in [36]. A decentralized control law for producing increased robot density in areas of more importance is presented in [37].

The paper [38] considers a swarm of micro-air vehicles (MAVs) that are launched by hand in a certain place of interest, so the MAVs can serve as a wireless relay for rescuers and victims in a disaster area. The MAVs flight follows a circling path with a moving center (just like some birds explore an area).

Coming back to exploration applications, let us cite some more contributions. Mostly for indoor applications, [39] presents a multi-robot cooperative approach, using cell decomposition, and having limited communication. The article [40] introduces a suggestive method for multi-robot coordinated exploration, forcing an adequate dispersion of robots towards unknown spaces.

Interesting applications are: mine detection using multi-agents [41], area surveillance with a swarm of MAVs [42], and area exploration based on pheronomes and bird flocks [43]. Extensive reviews on exploration can be found in [44].

If we now focus on search tasks, we find an interesting analysis of cooperative searching using UAV swarms in [45], which considers moving, possibly evading targets, and discusses the use of in-line or front formations. The coordination of several UAVs for cooperative searching, based on cell decomposition, occupancy probability, Bayesian treatment for data fusion, is presented in [46]. An extensive work on keeping swarm connectivity during searching has been done by [47]

5.0 ANTS

A paradigmatic example of natural swarms is ant colonies. Ants lay down pheromone trails, which serve for stigmergy: a mechanism of indirect coordination with other ants through the environment. Imitating ant colonies, path optimization algorithms have been proposed. There is an extensive literature on this topic, like for example [48, 49]. Interesting surveys of related research are [50, 51].

In our case, we are proposing to use a mix of explorer ants and forager ants. A special population dynamics has been imposed, so when the ants have found a good source of food, the number of explorers decrease, while when resources become scarce, the number of explorers increases. Since the TSP can be used as benchmark, we employed it for comparison with other algorithms. After an extensive study, our algorithm compares favorably with the most important existing algorithms, [52, 53].

We exploited the algorithm for planning ship paths in the presence of obstacles, with good results [13].

We did other experiments with the algorithm, finding that in applications where some hints can help, not much explorers are necessary; on the contrary, applications where only a purely random search is possible, the explorer population increases.

There are robotic versions of ants, using 'digital pheronomes', like in [54, 55] for the coordination of robotic swarms.

6.0 SWARMS

There is an extensive literature on swarms easily available from the web. We want only to do some comments, and to recommend some papers.

Coming to the roots, social insects provide a fundamental archetype of swarms. In this context, the article [56] gives a succinct and attractive analysis on collective behavior aspects.

A frequently cited technical report on swarm robotics is [57]. This document considers motivations and domains of applications of swarms. The Thesis [58], Harvard University, provides a good account of techniques associated to robotic swarms. A good modern overview is of swarm robotics is [59].

Based on a shape function, that makes remember 3D potentials, decentralized controllers are proposed by

[60] for shape generation with robotic swarms. One of the spectacular experiments shown in this paper consists on robotic swarms forming alphabet letters.

One of the difficult problems related to swarms is how to program either simulations or robotic demonstrations. A set of tools, including a language, is introduced in [61].

Natural swarms are usually confined in a certain 3D boundary. When one designs local rules for robotic swarms, something has to be done in order to get stable swarm sizes. For example, one could follow a paradigm consisting on attracting and repulsive virtual forces. This is part of the questions treated in the Thesis [62]. Almost immediately, a gas metaphor comes to mind. In [63], a robotic simulation of gases for a surveillance task (a long corridor) is proposed.

Associated with the aspect just commented is that usually, after launching the swarm, an adequate and rapid dispersion of the swarm is desired. It is proposed in [64] to use wireless signal intensity as a rough measure of distance to assist the swarm members. In [65], three dispersion algorithms are proposed which outperform prior approaches (this paper should be confronted with [66]).

Apart from ants, there are other social insects that show useful performances. For instance, there are some publications that propose bee-inspired swarms, like for instance [67]. The foraging strategy of bees is studied in [68]. This strategy maintains foraging activity on several resources at the same time.

Based on bacterial chemotaxis, [69] introduced a method for robots to navigate to sources of interest using gradients. An environmental monitoring application was proposed.

For practical applications, an important aspect is human interaction with robot swarms. A recent extensive survey of this topic is [70]. A special way of interaction is introduced in [71], in which mediators at the spatial center of the swarm (that form a torus around the mediator).

There are many more contributions that would be of interest. A review is provided by [72]. Recent advances of swarm robotics are surveyed in [73]. A most cited book on swarm intelligence is [74].

7.0 MILITARY PERSPECTIVE

In his article on swarms and the future of warfare, [75] emphasizes the groundbreaking importance of the monograph [76], 2005, which presented a view of the evolution of doctrinal forms of conflict as follows: melee, mass, maneuver, and swarm. The later is a new form that needs reflection and updating of military schemes, as it is discussed in [77].

A different, but associated dimension is how to handle robot swarms in military scenarios. Chronologically we would mention a series of related publications. [78] on swarm intelligence and C2. [79] on human swarm interaction for searching of radiation sources. In 2009, [80] on exerting human control over decentralized swarms, and [81] on a similar question. And in 2012, [82] proposed a tactical command approach, by decomposing the swarm into units.

A methodology for UAV swarm mission planning is presented in [83]. Other publications of interest are [84] on hybrid control of swarms of aquatic drones, and [85] on countermeasures. In effect, there is a defense problem when attacked by a swarm.

An example of great visual impact (there are videos on Internet) is the Iran's aquatic swarm initiative [86].

From just a technical point of view, we would like to put a kind of radical example of a non-adequate approach. One decides to acquire 100 quad-copters. They come with 100 radio control consoles. Then one hires 100 pilots to handle the consoles, and try to experimentally demonstrate swarm behaviors. We do not know how each pilot would recognize from distance what is his drone. We also suppose that any coordination would be by voice between pilots. Measurable results would be difficult to obtain.

An extra software layer or component should be added to the drones' on-board control (if any). The objective of this software would be to avoid the 100 consoles and pilots. Local control rules would take care of autonomous behavior and the interaction with others.

By the way, a recent Guiness World Record has been the flight of 100 drones in formation.

A possible basic way for controlling the swarm is to plan a convenient general path, and to use this path to assign to the individuals certain relative locations (with some tolerance) while the swarm moves.

As shown in a number of internet videos with many coordinated small drones, using formations of formations could simplify the control. See [87] for swarm control details.

9.0 CONCLUSION

In this paper we tried to include comments and experiences that could contribute for the meeting purposes. By means of selected references we hope that sufficient material for further exploration has been given. It seems that the questions suggested for the meeting are quite open for next research.

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