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Robot Swarming Applications

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Summary. This paper discusses the different modes of operation of a swarm of robots: (*i*) non-communicative swarming, (*ii*) communicative swarming, (*iii*) networking, (*iv*) olfactory-based navigation and (*v*) assistive swarming. I briefly present the state of the art in swarming and outline the major techniques applied for each mode of operation and discuss the related problems and expected results.

1 Introduction

Swarm robotics is a relative new field of research building upon the pioneering work by Reynolds [21], who simulated of a flock of birds in flight (using a behavioural model based on few simple rules and only local interactions). Since then the field has witnessed many developments applying different approaches for swarm aggregation, navigation, coordination and control. The huge variations in methods etc. has sparked also a discussion about the definition of swarm robotics. Sahin [22] provides the following criteria to distinguish swarm robotics research: a swarm consists of (*i*) a large number of (*ii*) homogenous (*iii*) autonomous (*iv*) relatively incapable or inefficient robots with (*v*) local sensing and communication capabilities.

In this paper I will discuss swarm robotics as it is viewed upon in the GUARDIANS project and indicate how the swarm satisfies the given criteria. The objective of the GUARDIANS project is to apply a swarm of robots in a warehouse in smoke. The project recently started within the EU-FP6 frame work 'Advanced Robotics'.

The swarm will be able to operate in several autonomous modes. In the basic mode the robots navigate on their own and do not communicate, but just react to each other's behavior, I call this *non-communicative* swarming. The *communicative* mode complements the basic non-communicative mode and allows 'higher' level cooperation, for instance coordinated navigation. The distinction between non-communicative and communicative mode is also referred to as between explicit and implicit communication [17]. However, implicit communication also includes stigmergy; the latter term designates swarm behaviours where agents are influenced by signs or traces left behind by fellow agents. Some authors [3] loosely define stigmergy so as to include the GUARDIANS' behavior, but in non-communicative mode the robots do not leave signs or signals behind.

The communicative and non-communicative modes are quite distinct, however they are not mutual exclusive. The swarm is to be applied in industrial environments where the reception of wireless signals is very variable and communication failures are to be expected. The robot swarm brings its own wireless communication network and expands the network as required. I define this novel swarm behaviour as the *networking* mode of the swarm, in this mode the robots build and maintain the wireless communication network.

The robots are also provided with an artificial nose to warn for chemicals. The nose also enables the individual robots as well as the swarm to apply *olfactory-based* navigation and chemical plume detection.

The robot swarm is to support rescue operations whilst the rescuing is done by a human being. Therefore the swarm has to assist and to accompany a human being, in this novel *assistive* mode the swarming behaviour is adapted to enable cooperation between the robot swarm and the human.

Below, in section 2, I will briefly review the state of the art in swarm robotics. Sections 3 to 7 discuss the different modes of operation of the GUARDIANS swarm: (*i*) non-communicative swarming, (*ii*) communicative swarming, (*iii*) networking, (*iv*) olfactory-based navigation and (*v*) assistive swarming. I will outline the major techniques and the related questions and problems for each mode of operation and the expected results.

2 Overview of the state of the art

Initial robot swarm research has focused on centralized and leader based [4] approaches or centralised motion planning [14, 2]. However, a large number of robots -Sahin's criterion (*i*)- generates very dynamic behavior for which central control is computationally expensive and hard; motion planning is neither apt. Recent research has the emphasis on autonomous robots (criterion (*iii*)) including behavioural-based robotics [1], artificial potential functions [20, 8], virtual agents or virtual structures [16] and probabilistic [24] methods. Besides bio-inspired models, control-theoretic approaches are currently researched as well. Some approaches use global information while others are based on local interactions and rules, Sahin's criterion (*v*). Overviews of recent advances and the state of the art in swarms can be found in [5, 23, 12] also a web database on swarm robotics related literature is currently being compiled at http://swarm-robotics.org/. Recent projects in the EU-FP6 frame work, dealing with robot swarms are: URUS, robots accompanying human visitors; IWARD robots assisting in a hospital; DUSTBOT, garbage collecting robots; μDRONES, flying robots; and VIEW-FINDER, search and rescue robots (the project mentioned in this paragraph are listed at http://cordis.europa.eu/ist/cognition/projects.htm).

3 Non-communicative swarming

Non-communicative swarming has to be achieved without central or on-line control. In non-communicative mode the swarm consists of homogeneous but anonymous robots, the latter means that the robots are able to recognise another robot as a robot but they cannot identify other robots as a particular individual with a unique name. The advantages of this approach are that the swarming behaviour is relatively independent of the number of robots that are active, making the swarm robust to failures of individuals and its size may vary considerably. A drawback is that as the swarm behavior depends on many parameters and is inherently complex, it is hard to fully predict the behaviour. Swarm research therefore usually aims at behaviour types of a general nature. The basic behaviours that can be generated in the non-communicative mode are:

1. Obstacle and Robot avoidance
2. Wall/Track following
3. Gradient following
4. Aggregation/Dispersal/Gathering/Clustering
5. Area Coverage
6. Basic Search/Exploration Behavior
7. Acquisition/Maintenance of Geometric Formations
8. Autonomous Navigation

Obstacle avoidance, wall/track following and gradient following are autonomous behaviours of individual robots independent of being part of a swarm; the swarm behaviour is fully determined by external factors. Swarm control usually focusses on aggregation/dispersal, area coverage, search/exploration and moving in geometric formations. Autonomous navigation requires that the robots have some map of the environment available. Collective navigation in non-communicative mode is based on a combination of individual navigation and maintaining a particular geometric formation.

3.1 The control model

In order to obtain the listed behaviours, the artificial potential force field method is applied. It was introduced by Krogh [10], refer to [8] for a modern description. For biological simulations often *self-propelled particle* (SPP) models are applied, they were first introduced by Vicsek [25] to simulate biological swarms. Whereas the potential fields method originates from field descriptions, the SPP models focus on describing the behavior of the individual agent similar to the model in [19]. The two approaches are some times referred to as Gaussian (integrative field based) and Lagrangian (individual based) [18]. Basically the two approaches are equivalent and should be able to generate the same behaviours. The advantage of the individual based SPP approach is that a swarm can be build up by simply adding more robots.

Formal studies of swarm control usually assume that each robot has *perfect* or global information, and knows the exact position of the other robots [20, 8] and [9]. However in practice a robot observes its environment including other robots with sensors and makes navigation decisions on this basis - Sahin's criterion (v). The applied sensor system determines the type and quality of the information and therefore has a considerable impact on the swarm behavior. The sensor information is fed into a control model, that governs the robots and the swarm.

Based on its observations, each robot a calculates a force $\overrightarrow{F_a}$, which is the generator of the new velocity vector of the robot. In its general form the control model depends on four terms:

$$\overrightarrow{F}_a = \sum_{g \in G} \overrightarrow{EA}_{(g,a)} + \sum_{o \in O} \overrightarrow{ER}_{(o,a)} + \sum_{r \neq a}^{Sw} \overrightarrow{IA}_{(r,a)} + \sum_{r \neq a}^{Sw} \overrightarrow{IR}_{(r,a)} \qquad (1)$$

The first two terms represent the external influences; $\overrightarrow{EA}_{(g,a)}$ is the *attraction* of goal g on robot a and $\overrightarrow{ER}_{(o,a)}$ is the *repulsion* caused by the obstacle $o \in O$ on robot a. The second pair consists of the internal forces, which originate amongst the robots in the swarm Sw: the attraction $\overrightarrow{IA}_{(r,a)}$ and repulsion $\overrightarrow{IR}_{(r,a)}$ between any swarm member r and robot a. This description is Lagrangian, however if one considers a to be a point and let it range over the two dimensional plane, (1) generates a force field, its characteristics of course depend on the functions applied. Usually, the functions for attraction and repulsion are chosen such that on large distances the attractions dominate while on short distances the repulsions dominate.

Returning to the list of basic behaviours, obstacle avoidance is governed by $\overrightarrow{ER}$ and robot avoidance by $\overrightarrow{IR}$. In gradient following, the term $\overrightarrow{EA}$ is determined by values collected in the environment; for instance when searching for a communication signal the inputs are the signal strengths in the field. The internal attraction and repulsion are sometimes called the artificial social potential functions [20]: their combination induces coherence in the swarm. At a particular distance internal attraction and repulsion balance; the aggregation, dispersal and clustering behaviours are obtained by selecting a particular balance.

4 Communicative swarming

Communication improves the abilities for swarm control considerably. This section assumes a communication network is simply available, the next section looks at establishing and maintaining the communication network. For communication based swarming several approaches can be found in the literature, with an abundance of multi-agent based approaches, refer to [7] for a recent overview. The essence of a multi-agent system are the negotiation protocols and mechanisms. In this paper I highlight swarm behaviours that do not require negotiations.

Obviously when the robots can communicate they may exchange information about their local environment, enabling better informed conclusions. In non-communicative mode the input values for the control model (1) originate from the robot itself. In communicative mode the robots may use the information of all other robots. This global aspect allows for some control aiming at cooperative behaviours, such as cooperative Search/Exploration, cooperative Area Coverage, cooperative Gradient Following and cooperative Formation Control.

The wireless communication technology also enables position detection. This is important since most position detection systems, for instance GPS, require satellite signals. However, the reception of satellite signals is likely to fail indoors. With positions known and the overall information available the swarm has the basic ingredients for map building, also some robots may act as temporary position beacons and one could even use the robot swarm to set out a complete triangulation of an area.

By introducing negotiations the robots can further coordinate their actions, and for instance build up a division of labour.

5 Networking

As indicated earlier, the well functioning of the wireless communication network is not self evident, and the robot swarm has to be able to build up and maintain the communication network itself. The robots have to check the strength of the wireless signal, and if the signal is too weak or lost they have to search for a (better) signal. At swarm level, searching for a wireless signal and building a network transfers into what is called *ad-hoc networking*. In ad-hoc networking the topology of the network changes as the circumstances require. A wireless communication network usually consists of network nodes and clients. The robots can act both as clients and as network nodes, thus while the swarm advances and when necessary some robots will act as network nodes. The result is a mobile ad-hoc network consisting of a set of adjustable and moving nodes which is typically self-organising and adapts to connection failures.

Various wireless communication technologies are available. They differ in network size, radio range, data rate and power consumption. Wireless LAN is suited to high data rate and high range communication at the cost of high power consumption. Bluetooth has a lower data rate and transmission range but in turn significantly lower power consumption. ZigBee is highly scalable with even lower power consumption but with a trade off for lower data rates. Ultra Wide Band UWB is promising but not yet fully available.

Mobile ad-hoc networks provide also a basis for collaboration as one can apply automatic service discovery. The latter means that the robots try to find peers in their vicinity to help them to solve a local problem [6]. The problem of efficient service discovery in mobile ad-hoc networks is still unsolved. Known solutions for service discovery were not designed with the high dynamics of a swarm network in mind.

6 Olfactory-based navigation

The Guardians robots are provided with a 'nose' to measure gas concentrations. This enables a broad range of applications: surveillance for environmental pollutants [15], the detection of hazardous gases and plume tracking but also navigation on self-produced odors (stigmergy)[13]. Relevant aims for the warehouse scenario are: signalling traces of chemicals, locating the source and tracking the chemical plume.

Alarming for toxic chemicals obviously helps safeguarding the human fire fighters. Locating the odor source can be done by individual robots in non-communicative mode as well by the swarm in communicative mode. Efficient swarming algorithms for terrain surveying based on spatial concentration of odor fields are developed. A plume is subject to diffusion and airflow and cannot be suppose to be static. Tracking a plume has to involve many robots and requires communication. Both olfactory-based communicative swarming (enabling efficient coverage of the area) and non-communicative olfactory-based swarming (robust fall-back option) are developed.

7 Assistive Swarming

Wireless communication also enables the robots to support a human squad-member operating within close range. The robots are autonomous, a feature with far stretching consequences for the human-robot interface: the human swarm interface is essentially very different from the human-robot interfaces applied in telerobotics. In telerobotics several humans may operate one robot, in Guardians however, it is basically one human being cooperating with several robots.

A first question to answer is whether the human squad-member is leading the swarm or whether the swarm is guiding the human being. Whether supporting or leading, the swarm of robots should in general not increase the navigation related load (physical or cognitive) [11] of the human being. This is even more true in the context of human robot interaction in a fire fighting situation. The smoke and the noisy breathing equipment, pose a difficult design problem for the human robot swarm interface. One cannot rely on the commonly used audio-visual communication means and the project is forced to look at other means to establish communication between the human and the robots. The objective of having a human participate in the swarm of robots is to add some qualities which are not inherently available in the robotic swarm. Swarm algorithms are built upon autonomous operations of the robots to which human originating tactical planning instructions might be added. Human control in swarm robotics allows for dynamic control of specific swarm activities based upon local circumstances and human expertise. In addition, feedback from local robots can enhance the task performance of the human being.

References

[1] T. Balch and R. C. Arkin. Behavior-based formation control for multirobot teams. *IEEETRA*, 14(6):926–939, December 1998.

[2] J. Barraquand, B. Langlois, and J. C. Latombe. Numerical potential field techniques for robot path planning. *IEEE Transactions on Systems, Man, and Cybernetics*, 22(2):224–241, 1992.

[3] G. Beni. From swarm intelligence to swarm robotics. In *Swarm Robotics: SAB 2004 International Workshop, Santa Monica, CA, USA, July 17, 2004, Revised Selected Papers*, pages 1–9. Lecture Notes in Computer Science, Springer Verlag, 2005.

[4] J. P. Desai, J. Ostrowski, and V. Kumar. Modeling and control of formations of nonholonomic mobile robots. *IEEETRA*, 17(6):905–908, December 2001.

[5] M. Dorigo and E. Sahin. Special issue on swarm robotics. *Autonomous Robots*, 17(2-3), September 2004.

[6] Jia Lei Du, Stefan Rührup, Ulf Witkowski, and Ulrich Rückert. Resource and service discovery for large–scale robot networks in disaster scenarios. In *Proceedings of the IEEE International Workshop on Safety, Security and Rescue Robotics (SSRR2005)*, Kobe, Japan, june 2005.

[7] Alessandro Farinelli, Luca Iocchi, and Daniele Nardi. Multi-robot systems: A classification focused on coordination. *IEEE Transactions on System Man and Cybernetics, part B*, pages 2015–2028, 2004.

[8] V. Gazi. Swarm aggregations using artificial potentials and sliding mode control. *IEEE Transactions on Robotics*, 21(6):1208–1214, 2005.

[9] S. Kazadi, M. Ching, B. Lee, and R. Cho. On the dynamics of clustering systems. *Robotics and Autonomous Systems*, 46(2):1–27, 2003.

[10] B. Krogh. A generalized potential field approach to obstacle avoidance control. In *SME conf. Proc. Robotics Research: The next five years and beyond*, pages 11–22, 1984.

[11] V. Kulyukin, C. Gharpure, J. Nicholson, and G. Osborne. Robot-asisted wayfinding for the visually impaired in structured indoor environments. *Autonomour Robot*, 21:29–41, 2006.

[12] V. J. Kumar, N. E. Leonard, and A. S. Morse, editors. *Cooperative Control: 2003 Block Island Workshop on Cooperative Control*, volume 309 of *Lecture Notes in Control and Information Sciences*. Springer-Verlag, 2005.

[13] S. Larionova, L. Marques, and A.T. de Almeida. Olfactory coordinated mobile robot area coverage. *Autonomous Robots Journal, Special Issue on Mobile Robot Olfaction*, 2006.

[14] M. Latombe. *Robot motion planning*. Kluwer Academic Press, 1991.

[15] L. Marques, N. Almeida, and A. T. de Almeida. Olfactory sensory system for odour-plume tracking and localization. In *Proc. IEEE Int. Conf. on Sensors*, Toronto, Canada, 2003.

[16] P. Ögren, E. Fiorelli, and N. E. Leonard. Formations with a mission: Stable coordination of vehicle group maneuvers. In *Symposium on Mathematical Theory of Networks and Systems*, August 2002.

[17] L. E. Parker. Current state of the art in multi-robot teams. In *Distributed Autonomous Robotic Systems 4*, pages 3–12, 2000.

[18] J.K. Parrish and W.M.(eds.) Hamner. *Animal groups in three dimensions*. Cambridge University Press, 1997.

[19] J.S.J.H. Penders, L.S. Alboul, and Braspenning P.J. The interaction of congenial autonomous robots: Obstacle avoidance using artificial potential fields. In *Proceeding ECAI-94*, pages 694–698. John Wiley and Sons, 1994.

[20] J. H. Reif and H. Wang. Social potential fields: A distributed behavioral control for autonomous robots. *Robotics and Autonomous Systems*, 27(3):171–195, May 1999.

[21] C. W. Reynolds. Flocks, herds, and schools: A distributed behavioral model. *Comp. Graph.*, 21(4):25–34, 1987.

[22] E. Sahin. Swarm robotics: From sources of inspiration to domains of application. In *Swarm Robotics: SAB 2004 International Workshop, Santa Monica, CA, USA, July 17, 2004, Revised Selected Papers*, pages 10–20. Lecture Notes in Computer Science, Springer Verlag, 2005.

[23] E. Sahin and W. M. Spears, editors. *Swarm Robotics, A State of the Art Survey*. Lecture Notes in Computer Science 3342. Springer-Verlag, Berlin Heidelberg, 2005.

[24] D.J. Stilwell, B.E. Bishop, and C.A. Sylvester. Redundant manipulator techniques for partially decentralized path planning and control of a platoon of autonomous vehicles. *IEEE Transactions on Systems Man and Cybernetics Part B-Cybernetics*, 35(4):842–848, 2005.

[25] T. Vicsek, A. Czirk, E. Ben-Jacob, and I. Cohen. Novel type of phase transition in a system of self-driven particles. *Physical Review Letters*, 75(6):1226–1229, 1995.