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Special issue on swarm robotics

Erol Şahin · Alan Winfield

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Swarm robotics is a new approach to the coordination of multi-robot systems. In contrast with traditional multi-robot systems which use centralised or hierarchical control and communication systems in order to coordinate robots' behaviours, swarm robotics adopts a decentralised approach in which the desired collective behaviours emerge from the local interactions between robots and their environment. Such emergent or self-organised collective behaviours are inspired by, and in some cases modelled on, the swarm intelligence observed in social insects.

The potential for swarm robotics is considerable. Any task in which physically distributed objects need to be explored, surveyed, collected, harvested, rescued, or assembled into structures is a potential real-world application for swarm robotics. The key advantage of the swarm robotics approach is robustness, which manifests itself in a number of ways. Firstly, because a swarm of robots consists of a number of relatively simple and typically homogeneous robots, which are not pre-assigned to specific roles or tasks within the swarm, then the swarm can self-organise or dynamically re-organise the way individual robots are deployed. Secondly, and for the same reasons, the swarm approach is highly tolerant to the failure of individual robots. Thirdly, the fact that control is completely decentralised means that there is no common-mode failure point or vulnerability in the swarm. Indeed, it could be said that the high level of robustness evident in robotic swarms comes for free in the sense that it is intrinsic to the swarm robotics approach, which contrasts with the high engineering cost of fault tolerance in conventional robotic systems.

The realisation of the potential of swarm robotics requires the solution of a number of very challenging problems. Firstly, in algorithm design: swarm roboticists face the problem of designing both the physical morphology and behaviours of the individual robots such that when those robots interact with each other and their environment, the desired overall collective behaviours will emerge. At present there are no principled approaches to the design of low-level behaviours for a given desired collective behaviour. Secondly, in implementation

E. Şahin (✉)
Middle East Technical University, Ankara, Turkey
e-mail: erol@ceng.metu.edu.tr

and test: to build and rigorously test a swarm of robots in the laboratory requires a considerable experimental infrastructure. Real-robot experiments thus typically proceed hand-in-hand with simulation and good tools are essential. Thirdly, in analysis and modelling: a robotic swarm is typically a stochastic, non-linear system and constructing mathematical models for both validation and parameter optimisation is challenging. Such models would surely be an essential part of constructing a safety argument for real-world applications.

There are, at the time of writing, no known real-world applications of swarm robotics and, given the challenges outlined above, this is perhaps not surprising. However, as the papers of this special issue demonstrate, the field of swarm robotics is developing very strongly, and we predict that real-world applications of swarm robotic systems will emerge in the near future.

A total of seventeen papers were submitted to this special issue and, following a rigorous process of anonymous review, eight have been selected for publication. The papers included in this special issue cover a broad spectrum of the challenges outlined above, from Design and Algorithms including self-assembly, self-organised flocking, self-organised distribution, evolutionary robotics and – with an applications focus – swarming of Micro Air Vehicles for communications relay. One paper focuses on a new generation of simulation tool, and two papers on new approaches to mathematical modelling and analysis. Outlined below, the eight papers of this special issue strongly represent the state-of-the-art in this vibrant field of research.

Design and algorithms

In the paper "Evolving coordinated group behaviours through maximisation of mean mutual information", Sperati et al. bring a novel evolutionary approach to the difficult problem of individual robot controller design for swarm robotic systems. The use of a genetic algorithm to evolve the low-level individual robot controller to optimise a fitness function which encodes the desired overall swarm behaviour is a well known and powerful approach. However, as Sperati et al. point out, there is no principled approach to designing the fitness function to reward coordinated swarm behaviour. To address this problem this paper proposes an information theoretic approach in which the fitness function is based upon the mean mutual information between the motor states of all possible robot pairs in the swarm. The paper describes a series of experiments, using both simulated and real *e-puck* robots, in which (in the majority of runs) structured and synchronised group behaviours of extraordinary richness emerge.

In "Self-organized flocking in mobile robot swarms", Turgut et al. describe how self-organised flocking can be achieved on a swarm of mobile robots. Pointing out that prior studies of flocking assumed either unrealistic sensing abilities that do not exist on current robots, or the existence of a common goal direction within the group, they successfully demonstrate truly self-organised flocking. Experiments using both simulation and real *Kobot* robots show that a swarm of mobile robots, initially connected via proximal sensing, is able to wander in an environment by moving as a coherent group in open space and to avoid obstacles as if it were a "super-organism".

In "Biologically inspired redistribution of a swarm of robots among multiple sites", Hsieh et al. are inspired by studies of ant colony nest site selection to develop a quorum based decentralised algorithm for allowing a swarm of robots to physically distribute themselves across multiple locations in a specified ratio. The algorithm is tested using idealised agents in simulation but, importantly, the paper also undertakes a thorough analysis, first mathematically modelling the system, then proving that it is stable and will converge to the target configuration.

In "SWARMORPH-script: A language for arbitrary morphology generation in self-assembling robots", Christensen et al. describe a script for specifying the rules which, when executed, enable a swarm of robots to self-assemble into a given morphology. The script is designed to be transmitted from one robot to another so that a partially assembled structure can recruit new robots to physically join the assembly, even though those robots had no a-priori knowledge of the morphology. The approach is completely decentralised in that robots cannot sense the shape or state of the emerging structures. Robots that are not part of a structure can only sense where and with what orientation they should physically attach to the structure; once attached, a robot then communicates with the robot to which it has joined in order to discover if and how it can locally extend the morphology. Importantly, this is not a theoretical exercise; the paper describes a series of experiments on real-robot hardware, using SWARMBOT *s-bot* robots, to demonstrate and validate the approach.

In their article "Ant-based swarming with positionless micro air vehicles for communication relay", Hauert et al. describe how a swarm of micro air vehicles (MAVs) could be deployed to create an ad hoc network in disaster areas to establish communication between multiple users on the ground. Using inspiration from army ants that are known to lay and maintain pheromone paths between their nest and food sources, they develop a method that does not require positioning information and uses only local communication by storing virtual pheromones deposited on MAVs. The proposed approach is demonstrated with a 3D simulation of fixed-wing MAVs.

Tools

In his article "Massively multi-robot simulation in Stage", Vaughan introduces the new version of Stage, an open-source multi-robot simulation platform that has been widely used in both teaching and research. Using a simple benchmark to measure the performance of the simulator, Vaughan shows that the speed of simulation scales approximately linearly with population size up to 100,000 robots and would constitute a serious tool for studying swarm robotic systems.

Modelling and analysis

In their article "A framework of space-time continuous models for algorithm design in swarm robotics", Hamann and Wörn propose a modelling framework that can explicitly represent space to take into account spatial inhomogeneity in swarm robotic systems. Within this framework, using methods from statistical physics to address spatiality, the authors are able to map the individual behaviours onto an abstract model of the swarm motion. They apply this framework to two case studies to show that qualitative correctness can be achieved.

In "Modelling a wireless connected swarm of mobile robots", Winfield et al. extend the probabilistic modelling approach by developing a macroscopic model for a swarm of wireless connected robots operating in unbounded space. The model predicts the macroscopic steady-state connectivity of the swarm from the low-level robot controller and its parameters, proposing first a probabilistic finite state machine (PFMS) model of connectivity and, secondly, a novel robot-centric approach for estimating the state transition probabilities.

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Erol Şahin
Alan Winfield