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Benchmark of swarm robotics distributed techniques in a search task

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HIGHLIGHTS

- A survey on multi-robot search inspired on swarm intelligence is presented.
- Five state-of-the-art swarm robotic algorithms are described and compared.
- Simulated experiments of a mapping task are carried out to compare the five algorithms.
- The three best performing algorithms are deeply compared using 14 e-pucks on a source localization problem.
- The Robotic Darwinian Particle Swarm Optimization (RDPSO) algorithm depicts an improved convergence.

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ABSTRACT

This paper presents a survey on multi-robot search inspired by swarm intelligence by further classifying and discussing the theoretical advantages and disadvantages of the existing studies. Subsequently, the most attractive techniques are evaluated and compared by highlighting their most relevant features. This is motivated by the gradual growth of swarm robotics solutions in situations where conventional search cannot find a satisfactory solution. For instance, exhaustive multi-robot search techniques, such as sweeping the environment, allow for a better avoidance of local solutions but require too much time to find the optimal one. Moreover, such techniques tend to fail in finding targets within dynamic and unstructured environments. This paper presents experiments conducted to benchmark five state-of-the-art algorithms for cooperative exploration tasks. The simulated experimental results show the superiority of the previously presented Robotic Darwinian Particle Swarm Optimization (*RDPSO*), evidencing that sociobiological inspiration is useful to meet the challenges of robotic applications that can be described as optimization problems (e.g., search and rescue). Moreover, the *RDPSO* is further compared with the best performing algorithms within a population of 14 e-pucks. It is observed that the *RDPSO* algorithm converges to the optimal solution faster and more accurately than the other approaches without significantly increasing the computational demand, memory and communication complexity.

1. Introduction

Search applications have been well studied in the past [1]. However, the use of multi-robot systems (*MRS*) to fulfill such missions has not yet received the proper attention. Nonetheless, *MRS* offer several advantages over single solutions, or even human rescuers, within search applications. Besides providing a natural fault-tolerance mechanism, the use of multiple robots is especially preferable when the area is either hazardous or inaccessible to humans, e.g., search-and-rescue (*SaR*) victims in catastrophic scenarios [2].

Similar to optimization problems in which one can distinguish exhaustive methods from biologically-inspired ones, *MRS* within search applications face the same dilemma: either decide on an exhaustive technique in which robots sweep the entire area [3], or mimic simple local control rules of several biological societies

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(e.g., ants, bees, birds) to stochastically search the scenario [4]. This last one is a typical feature from most *swarm robotics* algorithms [5]. Swarm robotics applied in search tasks can offer several major benefits over the conventional search techniques, such as: the robustness of the swarm to failure of individual units or run-time addition of new units, the scalability of emergent behaviors to swarms of different sizes, the leveraging of self-organization principles of environmental noise and individual differences, and the synergetic effect whereby the work of the swarm is greater than the sum of the work by the individual units, known as *superlinearity* [4]—a concept shared with other fields such as complex systems.

Although many different swarm robotics algorithms have been recently proposed in the literature, this work will focus on the ones that benefit from explicit over implicit communication, such as the work recently proposed by Kernbach et al. [6]. In algorithms under explicit communication, robots need to be able to explicitly exchange information within a network path using some sort of medium (e.g., wireless communication). Despite such a requirement, the choice of explicit communication over implicit or *through-the-world* interactions, also known as *stigmergy*, relies on the application domain of realistic search applications such as search-and-rescue (*SaR*). According to the current state-of-the-art in this field, robotic technology is used, almost exclusively, to assist and not substitute human responders. Hence, multiple mobile robots can take advantage of parallelism to reduce the time required to fulfill the mission while explicitly providing important data about the site (e.g., contextual information), whether accessible or inaccessible for human agents.

Moreover, this work will focus on distributed solutions. This is obvious within swarm robotics context in which tasks are inherently distributed in space, time, or functionality. Nevertheless, it should be noted that some works still emphasize on centralized architectures [7], thus moving away from the fully distributed nature inherent to the principles of collective intelligence. In practice, centralized swarm architectures are computationally expensive and unsuitable as a large number of robots usually generate very dynamic behaviors that a centralized controller cannot handle [8]. Also, centralized architectures lack robustness as the failure of the centralized entity may compromise the performance of the whole *MRS* [9].

Bearing these ideas in mind, this work presents an overview of distributed swarm robotics techniques under explicit communication constraints, applied to search applications, thus comparing them in both simulated environment and real experiments.

2. Swarm robotics in search applications

In nature, some complex group behaviors arise in biological systems composed of swarms that are observed in a variety of simple social organisms (e.g., ants, bees) [10]. One of the most relevant topics in *MRS* is the modeling and control of the population. Hence, the design of such bio-inspired swarm *MRS* requires the analysis of the social characteristics and behaviors of insects and animals.

To that end, Suarez and Murphy [2] recently presented a brief description of more than 50 papers on animal foraging making the analogy to *SaR* applications. Most works presented in this survey suggested that robots should divide the whole environment into patches, as many animals do, and then search within such patches. Nevertheless, and even as stated by the authors, victims can appear anywhere. Hence, the difficulty in subdividing a search environment and defining patches within unknown scenarios still remains. The authors also claim that *SaR* robotics should focus on exhaustive search as the motivation is different from animal foraging—while animals attempt to maximize their net energy level to stay alive, robots must find victims in a search area or determine that there are none to be found. However, although optimization may seem unsuitable for *SaR* robotics at first, there are some specific applications in which one can foresee its use like, for instance, in urban fires. Urban fires are probably the most frequent catastrophic incidents in urban areas, requiring a prompt response because of life endangerment in highly populated zones and the high risk of fire propagation to buildings and parked cars in the vicinity. An urban fire in a large basement garage often frequented by people and containing inflammable materials, like in a basement garage of a shopping mall with many cars, drivers and people passing by, is a particularly challenging *SaR* application because of the confined nature of the environment. As the fire evolves, the space becomes rapidly full of smoke, with very poor visibility and an unbreathable and toxic atmosphere, which is dangerous for both victims and first responders. Moreover, victims prone to such atmosphere would be unable to survive more than 10 to 20 min. Therefore, the use of exhaustive search strategies within this context would be unfeasible.

Actually, some works have recently focused on such scenarios, such as *Cooperation between Human and rObotic teams in catastroPhic Incidents* (*CHOPIN*) *R&D Project* [11]. The *CHOPIN* project aims at exploiting the human–robot symbiosis in the development of human rescuers' support systems for *SaR* missions in urban catastrophic incidents. One of the main catastrophic scenarios being used for proof of concept is the occurrence of fire outbreaks in large basement garages. In this case, the project focuses on using a fleet of cooperative ground mobile robots to cooperatively explore a basement garage where the fire is progressing, thus identifying the localization of fire outbreaks and victims.

One of the first approaches to fulfilling the objectives of this project was in dividing that kind of application into two operations: (i) *reconnaissance*; and (ii) *rescuing* [12]. In both phases, this kind of scenario usually poses radio propagation difficulties to the response teams, whose members usually wear a radio emitter/transmitter to communicate by voice. Often under these noisy scenarios, communication is only possible with teammates located in line-of-sight. Moreover, since a wireless communication computer network may be absent or damaged, robotic agents may have to deploy and maintain a mobile ad hoc wireless network (*MANET*) in order to support the interaction between the human team and the robotic team. In the *reconnaissance* phase, the mission consisted of a team of robots that arrived at the scenario via a common entry and spread out to explore and map the unknown area, signalizing possible points of interests such as victims and fire outbreaks. After a certain degree of confidence in the built representation of the scenario, the *rescuing* phase consisted of having the team of robots inspecting the area in a coordinated way, visiting all points of interest, looking for remaining victims, possible changes in the scenario and the evolution of fire outbreaks. The first approach was handled using a complete solution based on the well-known*Particle Swarm Optimization* (*PSO*) [13] to real mobile robots, denoted as *Robotic Darwinian PSO* (*RDPSO*), that was previously presented in [14] and further extended in [15,16].

Due to the successive improvements of the *RDPSO* and its positive outcome on several search tasks, now comes the time to benchmark it with state-of-the-art alternatives. Over the past few years, some algorithms initially designed to solve tasks such