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Editorial

Special Issue on Multi-Robot Systems: Challenges, Trends, and Applications

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1. Introduction

Multi-Robot Systems (MRSs) have emerged as a suitable alternative to single robots to improve current and enable new missions. These systems offer the following advantages over single robots:

- Effectiveness: In most scenarios, using a fleet of homogeneous robots improves the performance obtained by a single one. For instance, multiple robots can cover a larger area or spend less time than one robot in an exploration task.
- Efficiency: In a wide range of missions, using a heterogeneous fleet leads to more efficient management of resources than using a single robot. That is the case of fleets with aerial and ground robots applied to search tasks, where the aerial units can cover more terrain and make faster detections, but the ground ones can provide more accurate information of these detections.
- Flexibility: A multi-robot system can adapt to changes in the mission better than a single robot. These changes can be related to the scenario (e.g., scalability of mission area in search), tasks (e.g., fire control in environmental monitoring), or fleet (e.g., robots with difficulties during missions). The availability of resources allows replanning the missions to address these situations.
- Fault tolerance: This is a particular but relevant case where a multi-robot system is more flexible than a single robot. When a robot experiences problems, such as getting trapped in an obstacle or consuming all its battery, the rest can assume its functions.

However, multi-robot systems still face challenges related to robot autonomy and human factors. The deployment, operation, and collection of these systems in real-world scenarios need autonomy in the broad sense: robots with more capabilities and intelligence to operate longer in adverse conditions. In addition, the complexity of these systems poses some challenges to operators in terms of workload, situational awareness, and stress.

The recent literature on MRSs considers these challenges and proposes new strategies to face them. That is the case of artificial intelligence, which has given rise to new algorithms that allow managing the complexity and uncertainty of real scenarios, and immersive technologies (virtual and augmented reality), which are applied to facilitate the work of operators. These technologies are opening up a wide variety of missions, such as search and rescue, environmental monitoring, and many more.

In this "Special Issue on Multi-Robot Systems: Challenges, Trends, and Applications", we have collected a set of high-quality works that discuss the main challenges of MRSs, present the trends to address these issues, and report various relevant applications.

The remainder of this editorial is organized as follows: Section 2 discusses the challenges of MRSs, Section 3 addresses the proposals to solve them, and Section 4 describes the real-world applications presented in the different articles of the Special Issue.

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2. Challenges

The contributions to the Special Issue reveal a good amount of challenges for the operation of MRSs. Some are related to multi-agent mission planning, intervention in complex scenarios with uncertainty, and operation under restricted communications. Robot cooperation often helps deal with these issues through sharing information and coordinating actions. Kurt Geihs [1] reviews the state-of-the-art on teamwork in the context of multi-robot systems and dynamic environments. His paper identifies and analyzes multiple engineering challenges: dynamic coalitions, platform harmonization and configuration, knowledge base, methodology and tools, edge and cloud integration, and human in the loop and other sociotechnical concerns, among other concepts.

Rongye Shi, Peter Steenkiste, and Manuela M. Veloso [2] address the challenge of Multi-Agent Path Planning (MAPP), which is a resource allocation problem complicated by the highly dynamic and distributed environments. In contrast to most MAPP approaches, they assume soft collisions instead of hard collisions, which means that the agents can share resources or concur at the same location at the expense of reducing the quality of solutions. They propose the Soft-Collision M* (SC-M*) algorithm to solve these constrain satisfaction problems and compare its results with the most common algorithms in terms of path cost, success rate, and run time. Meanwhile, Yang Lyu, Quan Pan, and Jian Lv [3] address the problem of multi-robot collaborative self-localization in the context of target tracking missions. They propose an unscented transformation-based collaborative self-localization algorithm to deal with inter-robot and robot–target correlations during the missions.

Martin Juhás and Bohuslava Juhásová [4] address other relevant challenges for MRSs, which are communications and coordination. Their paper presents a time-synchronization solution for operations performed by a heterogeneous set of robotic manipulators grouped into a production cell. They develop a master–slave architecture without an external control element, whose communications are implemented via TCP/IP sockets. Similarly, Facundo Benavides, Caroline Ponzoni Carvalho Chanel, Pablo Monzón, and Eduardo Grampín [5] consider the multi-robot exploration problem under restricted communications. They propose a novel auto-adaptive multi-objective strategy to support the selection of tasks regarding both exploration performance and connectivity level. Compared with other algorithms, it shows effectiveness and flexibility to tackle the multi-robot exploration problem, decreasing the effects of disconnection periods without noticeable degradation of the exploration time.

Cooperation can be carried out in homogeneous fleets but also between robots with different morphology. Pablo R. Palafox, Mario Garzón, João Valente, Juan Jesús Roldán, and Antonio Barrientos [6] analyze air–ground robot cooperation in their paper. The combination of aerial and ground robots is useful in search and rescue tasks, given that aerial robots can provide valuable insight to support the navigation of ground robots in complex scenarios affected by disasters. The article proposes a state machine with algorithms that allow an aerial robot to take off, track, and land on a mobile ground platform.

Abhijeet Ravanka, Ankit A. Ravankar, Yohei Hoshino, and Yukinori Kobayashi [7] focus on another relevant challenge in multi-robot missions: uncertainty. They find information sharing as a powerful tool to deal with uncertainty in mission planning. In this way, when a robot finds a new obstacle or blocked path, it can share this information with the rest of the fleet, allowing other robots to plan better paths. The paper proposes a novel method for information sharing that works when robots have different sensors, there is positional uncertainty, and obstacles are dynamic. Aliakbar Akbari, Mohammed Diab, and Jan Rosell [8] also focus on uncertainty but in the context of mobile manipulation. In these applications, humans can collaborate with robots to execute complex actions, sharing their knowledge about the task and scenario. They propose a contingent-based task and motion planning method that generates trees of feasible plans considering robot uncertainty and human–robot interactions. This algorithm is validated in grasp tasks with occluding objects.

3. Trends

Currently, one of the most relevant multi-robot systems is swarms. David Garzón Ramos and Mauro Birattari [9] present an automatic method to design robot swarms. This method can generate control software by assembling preexisting software modules via optimization. They validate these developments with a swarm of e-pucks, which can use color-based information for handling events, communicating, and navigating. James Wilson, Jon Timmis, and Andy Tyrrell [10] address another relevant aspect of swarms: hormone systems for collective behaviors. They use a collection of virtual hormones to control the selection of behaviors that produce an effective foraging swarm.

Immersive technologies such as virtual, augmented, and mixed realities are usually proposed to improve operator workload, situational awareness, and performance. Ashish Kumar, Sugjoon Yoon, and V.R. Sanal Kumar [11] present a mixed reality simulation for Unmanned Aerial Vehicles in high-endurance missions of Earth exploration. This environment combines real and virtual quadcopters to monitor missions and find paths, among other things. Luis Pérez, Silvia Rodríguez-Jiménez, Nuria Rodríguez, Rubén Usamentiaga, and Daniel F. García [12] propose the creation of digital twins of manufacturing processes in Industry 4.0. In this way, a virtual reality testbed can be used to design, implement, and monitor the process in real-time before its physical development.

Finally, machine learning and especially reinforcement learning are increasingly popular for MRSs, especially for their operation in complex unstructured scenarios. Wenzhou Chen, Shizheng Zhou, Zaisheng Pan, Huixian Zheng, and Yong Liu [13] apply deep reinforcement learning for the collaborative formation and navigation of a robot fleet.

4. Applications

Robots are often applied in emergency scenarios because they can obtain information and even intervene, preventing dangers for human teams. Multi-robot systems are being introduced in these missions, such as outdoor and indoor fires. Juan Jesús Roldán-Gómez, Eduardo González-Gironda, and Antonio Barrientos [14] propose the use of drone swarms for the prevention, surveillance, and extinguishing of forest fires. This system consists of quadcopters that individually can visit waypoints and use payloads but, collectively, can perform complex tasks. The authors propose the use of immersive interfaces to allow operators to control multiple drones simultaneously.

However, emergency scenarios are not the only ones in which these systems can add value. Ángel Montes-Romero, Arturo Torres-González, Jesús Capitán, Maurizio Montagnuolo, Sabino Metta, Fulvio Negro, Alberto Messina, and Aníbal Ollero [15] propose a set of director tools for autonomous media production with a team of drones. They focus on a language for cinematography mission description and a procedure to translate missions into plans, so a media director that is not necessarily familiar with robots can manage the system.

Finally, multi-robot systems have also reached social robotics, although the need was not as clear as in other fields. Toshiaki Nishio, Yuichiro Yoshikawa, Kohei Ogawa, and Hiroshi Ishiguro [16] study multi-party conversations with two human-like robots. They focus on conveying information to the viewers through a natural conversation between the robots. Takamasa Iio, Yuichiro Yoshikawa, Mariko Chiba, Taichi Asami, Yoshinori Isoda, and Hiroshi Ishiguro [17] try a question-answer-response dialogue model with two humanoid robots to involve elderly users in the conversation. The results suggest that the presence of two robots might likely encourage elderly people to sustain longer talks.

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References

1. Geihs, K. Engineering Challenges Ahead for Robot Teamwork in Dynamic Environments. *Appl. Sci.* **2020**, *10*, 1368. [CrossRef]
2. Shi, R.; Steenkiste, P.; Veloso, M. SC-M*: A Multi-Agent Path Planning Algorithm with Soft-Collision Constraint on Allocation of Common Resources. *Appl. Sci.* **2019**, *9*, 4037. [CrossRef]
3. Lyu, Y.; Pan, Q.; Lv, J. Unscented Transformation-Based Multi-Robot Collaborative Self-Localization and Distributed Target Tracking. *Appl. Sci.* **2019**, *9*, 903. [CrossRef]
4. Juhás, M.; Juhásová, B. Synchronization of Heterogeneous Multi-Robotic Cell with Emphasis on Low Computing Power. *Appl. Sci.* **2020**, *10*, 5165. [CrossRef]
5. Benavides, F.; Ponzoni Carvalho Chanel, C.; Monzón, P.; Grampín, E. An Auto-Adaptive Multi-Objective Strategy for Multi-Robot Exploration of Constrained-Communication Environments. *Appl. Sci.* **2019**, *9*, 573. [CrossRef]
6. Palafox, P.; Garzón, M.; Valente, J.; Roldán, J.; Barrientos, A. Robust Visual-Aided Autonomous Takeoff, Tracking, and Landing of a Small UAV on a Moving Landing Platform for Life-Long Operation. *Appl. Sci.* **2019**, *9*, 2661. [CrossRef]
7. Ravankar, A.; Ravankar, A.; Hoshino, Y.; Kobayashi, Y. On Sharing Spatial Data with Uncertainty Integration Amongst Multiple Robots Having Different Maps. *Appl. Sci.* **2019**, *9*, 2753. [CrossRef]
8. Akbari, A.; Diab, M.; Rosell, J. Contingent Task and Motion Planning under Uncertainty for Human–Robot Interactions. *Appl. Sci.* **2020**, *10*, 1665. [CrossRef]
9. Garzón Ramos, D.; Birattari, M. Automatic Design of Collective Behaviors for Robots that Can Display and Perceive Colors. *Appl. Sci.* **2020**, *10*, 4654. [CrossRef]
10. Wilson, J.; Timmis, J.; Tyrrell, A. An Amalgamation of Hormone Inspired Arbitration Systems for Application in Robot Swarms. *Appl. Sci.* **2019**, *9*, 3524. [CrossRef]
11. Kumar, A.; Yoon, S.; Kumar, V. Mixed Reality Simulation of High-Endurance Unmanned Aerial Vehicle with Dual-Head Electromagnetic Propulsion Devices for Earth and Other Planetary Explorations. *Appl. Sci.* **2020**, *10*, 3736. [CrossRef]
12. Pérez, L.; Rodríguez-Jiménez, S.; Rodríguez, N.; Usamentiaga, R.; García, D. Digital Twin and Virtual Reality Based Methodology for Multi-Robot Manufacturing Cell Commissioning. *Appl. Sci.* **2020**, *10*, 3633. [CrossRef]
13. Chen, W.; Zhou, S.; Pan, Z.; Zheng, H.; Liu, Y. Mapless Collaborative Navigation for a Multi-Robot System Based on the Deep Reinforcement Learning. *Appl. Sci.* **2019**, *9*, 4198. [CrossRef]
14. Roldán-Gómez, J.; González-Gironda, E.; Barrientos, A. A Survey on Robotic Technologies for Forest Firefighting: Applying Drone Swarms to Improve Firefighters' Efficiency and Safety. *Appl. Sci.* **2021**, *11*, 363. [CrossRef]
15. Montes-Romero, Á.; Torres-González, A.; Capitán, J.; Montagnuolo, M.; Metta, S.; Negro, F.; Messina, A.; Ollero, A. Director Tools for Autonomous Media Production with a Team of Drones. *Appl. Sci.* **2020**, *10*, 1494. [CrossRef]
16. Nishio, T.; Yoshikawa, Y.; Ogawa, K.; Ishiguro, H. Development of an Effective Information Media Using Two Android Robots. *Appl. Sci.* **2019**, *9*, 3442. [CrossRef]
17. Iio, T.; Yoshikawa, Y.; Chiba, M.; Asami, T.; Isoda, Y.; Ishiguro, H. Twin-Robot Dialogue System with Robustness against Speech Recognition Failure in Human-Robot Dialogue with Elderly People. *Appl. Sci.* **2020**, *10*, 1522. [CrossRef]