Multi-Robot Systems

Subjects: Robotics

Contributor: Jameela Al-Jaroodi

When applications require the integration and collaborative efforts of several robots, the collective of robots is referred to as a Multi-Robot System (MRS).

Keywords: robots ; multi-robot systems (MRS) ; multi-robot networks (MRNs) ; Middleware ; Collaborative robots

1. Introduction

The recent technological advances in robotics has opened the door for many useful automation applications in diverse domains. These advances include major enhancements in sensing, actuating, processing, analyzing, communications, recognition, leaning, perception, and controlling capabilities. With such advancements, many applications can be enhanced for better productivity, accuracy, quality, reliability, cost-effectiveness, flexibility, and safety using robots or robotic systems. For example, these capabilities facilitated the development of advanced industrial robot systems that automate and enhance manufacturing processes to produce more products with better accuracy and quality in cost-effective manners. They also allowed for the development of farming robots to handle agricultural processes and increase productivity, thus reducing the costs of farming and increasing accuracy in handling crops. Furthermore, they can be used as maintenance robots to perform inspections and repair tasks in difficult and dangerous places such as in underwater facilities and infrastructures spanning rough and inaccessible terrains. Moreover, they can be security robots that support the monitoring of important infrastructures such as oil, gas, and water pipelines and power stations. All these and many other applications will emerge and become more common in the near future as the driving technologies in robotics and supporting systems mature.

While some applications require the use of a single robot (or several independent robots) to effectively automate and enhance a process, there are others that require using multiple robots working together to achieve certain objectives in more cost-effective or/and efficient manners. Multiple robots used for any of these applications can be combined in what is referred to as a Multi-Robot System (MRS). It is worth noting that some researchers use the term Multi-Robot Network (MRN). Any MRS has several robots working together to achieve a certain application objective. Using an MRS over a single robot provides many benefits [1][2]:

- Multiple robots can concurrently work on the task to achieve it faster.
- Robots can be heterogenous in their capabilities to provide a cost-effective solution to achieve a task where each robot handles specific components of the task matching its capabilities.
- Multiple robots can effectively deal with a task that is inherently distributed over a wide area.
- Using multiple robots for achieving a task provides fault tolerance as the presence of multiple robots capable of similar processes can be used to compensate when any of them fails.

There are many research efforts in investigating different issues in MRS and providing solutions for these issues. The issues include task allocation [3], distributed intelligence [4], learning [5][6], coordination [7], coalition formation [8], motion planning [9] and middleware support [10]. In addition, there are some research efforts dedicated for developing application-specific solutions and algorithms for MRS such as patrolling algorithms [11], map merging [12], box-pushing [13], and flocking [14]. However, there is little effort in investigating the communication and networking aspects of MRS. Yet, communication and networks represent the main enabling technology for MRS applications. Robots in an MSR are connected with a network and the performance of this network has direct impact on most other solutions in MRS as well as the final performance of the applications. Some of the available work in this area focus on studying some theoretical aspects of MRS such as communication complexity [15] and localization [16]. In addition, there are some efforts to study specific communication issues for specific types such as small, low-power, low-cost MRS [17] and UAVs [18].

2. Types of MRS Systems and Their Applications

2.1. Types of MRS Systems

In general, there are two types of MRS systems [1].

2.1.1. Collective Swarm Systems

This type is characterized by having a typically large number of mobile robots which execute their own tasks based on local control laws leading to coherent team behavior. They require minimal communication with other robots.

2.1.2. Intentionally Cooperative Systems

This type is characterized by robots that have a knowledge of the presence, state, actions, and capabilities of other robots in the team. They work together to accomplish the same objective. This type of robots is further divided into two categories: (1) Weakly cooperative and (2) Strongly cooperative. This classification is based on the extent to which the actions of each robot is affected by the state and behavior of other robots in the team.

- *Strongly cooperative:* In this class of MRS systems, the robots act cooperatively to achieve a common goal. Consequently, this kind of close coordination require appropriate communication and synchronization which typically has more stringent quality of service (QoS) requirements such as bandwidth, and delay.

- *Weakly cooperative:* In this class of MRS systems, the robots divide and coordinate the tasks that need to be done among themselves. Afterwards, each robot proceeds to achieve its task with a form of operational independence. In this case, the supporting communication protocols and corresponding QoS requirements are more relaxed.

Furthermore, intentionally cooperative MRS systems can have heterogeneous robot members, which vary in sensing and acting capabilities. Consequently, they are different than the collective swarm systems, due to the fact that the robots belonging to a certain team are no longer interchangeable.

2.2. MRS Applications

There are several applications that can be improved using MRS. Some of these applications are search and rescue [19][20], detection of forest fires [21], hazardous waste removal [22], farm operations [23], mining [24], constructions [25], disaster management [26], security applications [26][27], warehouse management [28], moving containers within harbors and airports [29], and gaming and entertainment such as soccer [30].

3. MRS Architectures

Various major architectures can be identified for MRS systems [1]. Such architectures significantly affect the robustness, reliability, and scalability of the system, and are dictated by the strategy used to make decisions, manage the interactions between the robots, and generate the group behavior of the team.

- *Centralized*: In this category a single point of control manages the behavior of all the robots in the team [31]. Such architecture suffers from the single point of failure problem, which can reduce its reliability. Also, the scalability is diminished. This is because the central controller must be constantly aware of the state of the all the team members which triggers the exchange of numerous messages in addition to the control messages which must also be sent back to the individual robots to control their actions.

- *Hierarchical*: In this category, the robots are organized in a command and control hierarchy similar to that in the military. Specifically, in this strategy, a robot controls a group of other robots. Each of those robots in turn controls a group of other robots. This pattern can continue for several levels down the hierarchy depending on the size of the network. This approach, it is highly scalable and can be appropriate for some applications with a large number of robots. However, it has reduced reliability due to the considerable vulnerability in handling failures of robots at the higher levels in the hierarchy.

- *Decentralized*: This is the most common category for MRS systems. In this case, robots take actions based on their own local view following certain strategic guidelines and goals for the team. This model is characterized by its robustness and ability to adjust to failures, since no centralized control is used. On the other hand, it is a challenge to keep the synchronization and coherency among the robots. In addition, it is not trivial to coordinate actions when mission objectives change.

- *Hybrid*: This approach combines a local decentralized control, which provides robustness with hierarchical control to achieve global synchronization and coordination of actions, goals, and tasks. This hybrid strategy is used in many MRS systems, which need to have scalability due to the large size of the network as well as an ability to take quick decisions on the local level to achieve better performance and quicker reaction to local events and failures.

References

1. Parker, L.E. Multiple mobile robot systems. In Springer Handbook of Robotics; Springer: Berlin, Germany, 2008; pp. 921–941.
2. Zlot, R.; Stentz, A.; Dias, M.B.; Thayer, S. Multi-robot exploration controlled by a market economy. In Proceedings of the IEEE International Conference on Robotics and Automation, ICRA'02, Washington, DC, USA, 11–15 May 2002; Volume 3, pp. 3016–3023.
3. Gerkey, B.P.; Matarić, M.J. A formal analysis and taxonomy of task allocation in multi-robot systems. Int. J. Robot. Res. 2004, 23, 939–954.
4. Parker, L.E. Distributed intelligence: Overview of the field and its application in multi-robot systems. J. Phys. Agents 2008, 2, 5–14.
5. Matarić, M.J. Learning in behavior-based multi-robot systems: Policies, models, and other agents. Cognit. Syst. Res. 2001, 2, 81–93.
6. Wu, J.; Xu, X.; Wang, J.; He, H.G. Recent advances of reinforcement learning in multi-robot systems: A survey. Control Decis. 2011, 26, 1601–1610.
7. Yan, Z.; Jouandeau, N.; Cherif, A.A. A survey and analysis of multi-robot coordination. Int. J. Adv. Robot. Syst. 2013, 10, 399.
8. Vig, L.; Adams, J.A. Multi-robot coalition formation. IEEE Trans. Robot. 2006, 22, 637–649.
9. Bhattacharjee, P.; Rakshit, P.; Goswami, I.; Konar, A.; Nagar, A.K. Multi-robot path-planning using artificial bee colony optimization algorithm. In Proceedings of the 2011 Third World Congress on Nature and Biologically Inspired Computing (NaBIC), Salamanca, Spain, 19–21 October 2011; pp. 219–224.
10. Mohamed, N.; Al-Jaroodi, J.; Jawhar, I. A review of middleware for networked robots. Int. J. Comput. Sci. Netw. Secur. 2009, 9, 139–148.
11. Portugal, D.; Rocha, R. A survey on multi-robot patrolling algorithms. In Technological Innovation for Sustainability; Springer: Berlin/Heidelberg, Germany, 2011; pp. 139–146.
12. Carpin, S. Fast and accurate map merging for multi-robot systems. Auton. Robot. 2008, 25, 305–316.
13. Wang, Y.; De Silva, C.W. Multi-robot box-pushing: Single-agent Q-learning vs. team Q-learning. In Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, China, 9–15 October 2006; pp. 3694–3699.
14. Antonelli, G.; Arrichiello, F.; Chiaverini, S. Flocking for multi-robot systems via the null-space-based behavioral control. Swarm Intell. 2010, 4, 37.
15. Klavins, E. Communication complexity of multi-robot systems. In Algorithmic Foundations of Robotics V; Springer: Berlin/Heidelberg, Germany, 2004; pp. 275–292.
16. Pugh, J.; Martinoli, A. Relative localization and communication module for small-scale multi-robot systems. In Proceedings of the 2006 IEEE International Conference on Robotics and Automation, ICRA 2006, Orlando, FL, USA, 14–19 May 2006; pp. 188–193.
17. Fink, J. Communication for Teams of Networked Robots. Ph.D. Thesis, University of Pennsylvania, Philadelphia, PA, USA, 2011.
18. Jawhar, I.; Mohamed, N.; Al-Jaroodi, J.; Agrawal, D.P.; Zhang, S. Communication and networking of UAV-based systems: Classification and associated architectures. J. Netw. Comput. Appl. 2017, 84, 93–108.
19. Murphy, R.R. Marsupial and shape-shifting robots for urban search and rescue. IEEE Intell. Syst. Appl. 2000, 15, 14–19.
20. Waharte, S.; Trigoni, N.; Julier, S. Coordinated search with a swarm of UAVs. In Proceedings of the 6th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks Workshops, SECON Workshops '09, Rome, Italy, 22–26 June 2009; pp. 1–3.

21. Merino, L.; Caballero, F.; Martínez-de Dios, J.R.; Ferruz, J.; Ollero, A. A cooperative perception system for multiple UAVs: Application to automatic detection of forest fires. J. Field Robot. 2006, 23, 165–184.
22. Wagner, I.A.; Bruckstein, A.M. Cooperative cleaners: A study in ant robotics. In Communications, Computation, Control, and Signal Processing; Springer: Berlin, Germany, 1997; pp. 289–308.
23. Noguchi, N.; Will, J.; Reid, J.; Zhang, Q. Development of a master–slave robot system for farm operations. Comput. Electron. Agric. 2004, 44, 1–19.
24. Yinka-Banjo, C.; Bagula, A.; Osunmakinde, I.O. Autonomous Multi-robot Behaviours for Safety Inspection under the Constraints of Underground Mine Terrains. Ubiquitous Comput. Commun. J. 2012, 7, 1316.
25. Stroupe, A.; Huntsberger, T.; Okon, A.; Aghazarian, H.; Robinson, M. Behavior-based multi-robot collaboration for autonomous construction tasks. In Proceedings of the 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2005, Edmonton, AB, Canada, 2–6 August 2005; pp. 1495–1500.
26. Maza, I.; Caballero, F.; Capitán, J.; Martínez-de Dios, J.R.; Ollero, A. Experimental results in multi-UAV coordination for disaster management and civil security applications. J. Intell. Robot. Syst. 2011, 61, 563–585.
27. Guo, Y.; Parker, L.E.; Madhavan, R. Towards collaborative robots for infrastructure security applications. In Proceedings of the 2004 International Symposium on Collaborative Technologies and Systems, San Diego, CA, USA, 18–23 January 2004; pp. 235–240.
28. Correll, N.; Bekris, K.E.; Berenson, D.; Brock, O.; Causo, A.; Hauser, K.; Okada, K.; Rodriguez, A.; Romano, J.M.; Wurman, P.R. Analysis and observations from the first amazon picking challenge. IEEE Trans. Autom. Sci. Eng. 2016, 15, 172–188.
29. Alami, R.; Fleury, S.; Herrb, M.; Ingrand, F.; Robert, F. Multi-robot cooperation in the MARTHA project. IEEE Robot. Autom. Mag. 1998, 5, 36–47.
30. Kitano, H.; Asada, M.; Kuniyoshi, Y.; Noda, I.; Osawa, E. Robocup: The robot world cup initiative. In Proceedings of the First International Conference on Autonomous Agents, Marina del Rey, CA, USA, 5–8 February 1997; pp. 340–347.
31. Khoshnevis, B.; Bekey, G. Centralized sensing and control of multiple mobile robots. Comput. Ind. Eng. 1998, 35, 503–506.