Multi-Human Multi-Robot Interaction: Cooperation Leveraging a Robot Swarm as a Shared Resource

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***Abstract*— This paper investigates the ability of multiple operators to dynamically share the control of robot swarms and the effects of different communication types on performance and human factors. A total of 52 participants completed an experiment in which they were randomly paired to work together in guiding the swarm to complete spatially distributed tasks. Results show that although the ability to share robots did not necessarily increase task scores, it allowed the operators to switch between working independently and collaboratively, reduced the total energy consumed by the swarm, and was considered useful by the participants. We validate the sharing of robots among two operators using physical robots, demonstrating its applicability in the real world.**

I. INTRODUCTION

Simultaneously controlling multiple groups of robot swarms can be challenging for a single human operator as it may exceed their cognitive capacity [1], [2]. By involving multiple operators, each operator can focus on controlling a specific sub-swarm, which helps distribute the experienced cognitive workload. They could also send or receive some of their robots with each other in response to changing task demands (see Fig. 1). However, research on such multi-human-swarm systems is still scarce in the field [3].

We investigate the ability of two human operators to share the control of a swarm to complete tasks scattered across an environment. Previously, we developed a framework [4] and further extended it [5] with a novel user interface that allows each operator to navigate the environment through a first-person view provided by a local camera feed, and request from or send robots to the other operator (see Section II). In this paper, we demonstrate how a pair of human operators can share the swarm using real robots (see Section III).

II. SHARING ROBOTS IN A SIMULATED ENVIRONMENT

Our experiment followed a 2×2 mixed factorial design [6], where the robot-sharing condition (robot-sharing [RS] vs. no-robot-sharing [NRS]) was the within-subjects factor and the communication type (direct [DIR] vs. indirect [IND]) was the between-subjects factor (see Fig. 2). The operators interacted with a simulated robot swarm running in ARGoS [7] through a custom graphical user interface based on Webviz [2][1].

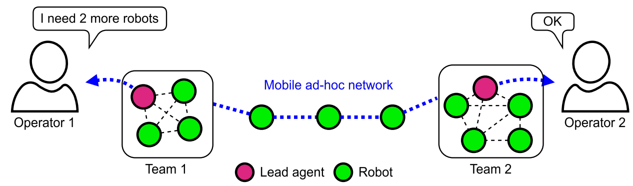

Fig. 1. Illustration of two human operators each guiding a subset of the robot swarm (e.g. a team) via a lead agent. Other robots maintain connectivity between the two teams. An operator can request robots from the other operator via the network maintained by the robots [5].

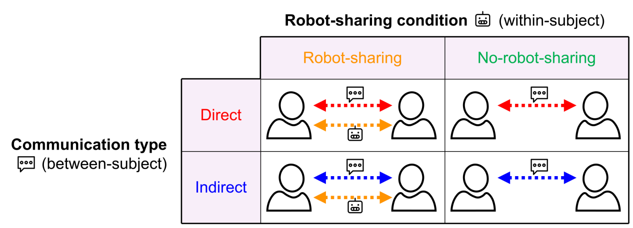

Fig. 2. Illustration of the 2×2 mixed factorial design conducted in this study. Red and blue dashed arrows between participants indicate the communication type. Orange dashed arrows are shown if the participants were able to send robots to each other.

We recruited 52 participants for this study. All participants were staff and students at the University of Sheffield. For a detailed description of the robot's behaviours, the graphical user interface and the experiment procedure, we refer to the original work where they were introduced in [5].

Results showed that teams using DIR communication were able to perform more tasks than those using IND communication. While the ability to share robots did not necessarily increase task scores, it significantly reduced the total distance travelled by the robots.

The post-trial questionnaire responses revealed that the participants found the ability to share robots with their partners useful and easy to use. One participant reported that "sharing robots allowed each team greater independence and versatility, while also enabling teamwork", which highlights the flexibility of being able to work independently and collaboratively depending on the situation.

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[1]The code used for the study is available from the following link: https://github.com/openswarm-eu/multi-human-swarm-control.

(a) (b)

Fig. 3. Tasks and actors: (a) Red cylindrical objects, used to represent tasks, and Pi-puck robots. Each object and Pi-puck have an ArUco marker that is detected by the overhead camera. (b) Each operator interacts with the user interface and guides one of the robots representing lead agents.

When asked about their strategy during the trials, many of the highest-scoring teams in IND communication reported that they often tried to anticipate their own needs as well as their partners. Since the size of the task area was relative to the number of robots required to complete it, one participant commented that they would "estimate the size (number of robots required) to anticipate the number [of robots] I would send" to their partner. This highlights the importance of maintaining a shared mental model among team members; having a good understanding of the partner's actions improves their own decision-making as they can predict when it is likely for their partner to make a request.

We also observed role-specialisation emerge in some teams. One participant reported that they would "have a team member with more robots [complete] larger tasks while the other moved around doing tasks that required fewer robots".

III. SHARING ROBOTS IN THE REAL WORLD

We used the Pi-puck robots [8] to validate the framework on a physical platform (see Fig. 3a). Each Pi-puck and task object had an ArUco marker [9]. Each operator was assigned to teleoperate a leader robot equipped with a Raspberry Pi camera module. This provided a local view of the surrounding environment and was presented to the operator via the user interface (see Fig. 3b).

Tasks were represented by red cylinder objects (see Fig. 3a), which indicated the task centres. Each task had a circular area with a radius of $0.2\sqrt[3]{n^{\min}}$ m from the task centre. Task objects were made taller than the Pi-pucks so that an operator could find a task even when other robots surrounded the leader robot.

Fig. 4 illustrates the overview of the system setup. An overhead camera was attached 1.5 m above the centre of the arena floor. The camera was connected to a central server, which detected the positions and orientations of individual ArUco markers attached to the robots, task objects, and two arena corners using Python and OpenCV [10].

The robots communicated with the server via a Wi-Fi network (using WebSockets) to exchange messages with other robots. Inter-robot communication was handled by the server, allowing a pair of robots to exchange messages if the distance between the respective ArUco markers was less than the specified communication range. The server also automatically determined whether the robots were located within a task area.

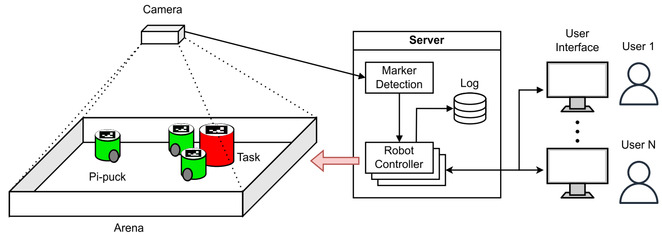

Fig. 4. System overview. The overhead camera captures the global positions and orientations of Pi-pucks and task objects. The server provides localised information to each robot controller. A user can connect to a robot via the interface to interact with the swarm.

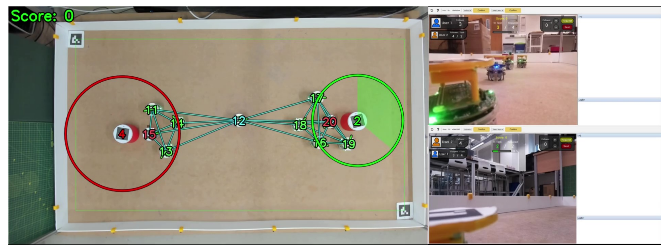

Fig. 5. Snapshot of the system. (left) Overhead camera view with information overlaid. Red and green circles represent tasks that have yet to be performed or partially completed, respectively. Numbers at the task centres indicate the number of robots needed to complete it. Other numbers represent robot IDs, where the red and green colours represent a leader and a follower robot, respectively. (right) The user interface of each operator.

We used the same interface that was used in the user study. Each interface was connected to a specific leader robot using WebSockets allowing the operator to move, send or receive messages. In total, 5 tasks (each requiring 1 to 5 robots to complete) were randomly placed in the arena.

Fig. 5 shows a snapshot during a trial[2]. The operators were allowed to interact with each other and the swarm via the interface and did not have access to the overhead camera view. Similarly to the user study, the operators guided the robots towards the tasks and shared robots with each other via the user interface when necessary. The operators successfully completed all five tasks in 2 min 29 s.

IV. CONCLUSION

We conducted a user study to investigate the effects of dynamically sharing robots between two human operators. Although sharing robots did not necessarily increase task scores, it provided the operators with the flexibility to work independently or collaboratively, reduced the energy consumed by the swarm (i.e. the total distance travelled), and was considered useful by the operators. We also validated human operators sharing the swarm using physical robots.

Future work will explore proximal interaction (i.e. human operators working alongside the robots), the sharing of robots among more than two operators and heterogeneous swarms.

[2] Video recording of this trial can be found in the following link: `https://youtu.be/Qblr1n8HXBY`.

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