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Teleoperating Multi-Robot Furniture

Exploring methods to remotely arrange multiple furniture robots deployed in a multi-use space

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Abstract. This paper presents the first study evaluating methods in remote teleoperation of multi-robot furniture for realistic applications. In a within-subjects user study (N=12), we tested two robot control methods designed to work at different levels of abstraction in a custom web-based user interface (UI): clicking and dragging to indicate a desired position and orientation for a single ChairBot ("set goal"), and selecting from a list of preset arrangements for multiple ChairBots ("select arrangement"). Participants were asked to use this UI to rearrange ChairBots in a living room across three birthday-themed arrangement prompts. We found overlapping preferences for how distinct participants set of the room for particular party phases, and received high experience and usability ratings for the novel web-based multi-ChairBot controller design. Self-reported survey responses suggest that our design is easy to learn and usable. Our works provides insight to future controls design for and research on multi-robot furniture systems.

Keywords: Robot Furniture · Teleoperation · Multi-Robot Systems

1 Introduction

Since Sirkin's Mechanical Ottoman [14], the number of robots with furniture morphologies in human-robot interaction (HRI) studies has rapidly increased. In fact, intelligent embodied devices of numerous classifications and purposes are now commonplace. A tech savvy consumer can program cookware, have robots to clean their floor, setup their front door to unlock at their presence, and automatically change the hue of their lights while they prepare for bed. Each of these systems requires careful interface design, and human-in-the-loop control schemes.

In this work, we synthesize prior work on robotic teleoperation, and robot furniture to design an interface for effectively arranging three chair robots (ChairBots) to explore furniture as a novel application for multi-robot systems. While previous work has demonstrated the ability of robot furniture to communicate with humans via motion [1,9,14], this paper presents the first study evaluating a multi-robot ChairBot system in a particular context: a multi-phase event in which the robots are controlled by a remote operator.

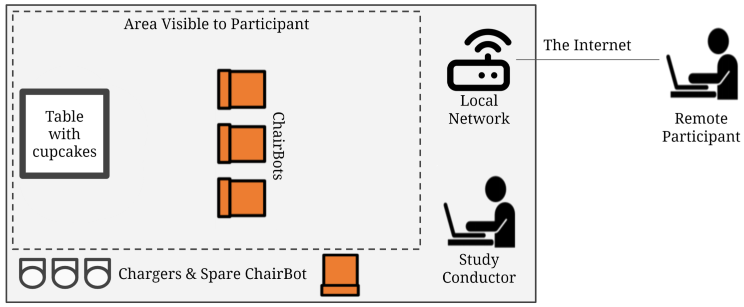

Fig. 1: A remote study participant interfaces with the system using the web UI with an overhead view of the area. A researcher locally monitors the ChairBots.

In a within-subjects user study (N=12), we tested two robot control methods designed to work at different levels of abstraction in a custom web user interface (UI): lower-level clicking and dragging to indicate a desired position and orientation for a single ChairBot ("set goal"), and higher-level selecting from preset arrangements for all ChairBots ("select arrangement"). Participants were asked to use this UI to rearrange ChairBots in a living room across three arrangement prompts based on phases of a birthday party. The goal was to explore the following research questions and associated hypotheses:

RQ1: Is furniture re-arrangement a viable application for teleoperated robots?

- H1: Participants will be **able to create furniture arrangements** that they self-report to be satisfied with given the prompt.
- H2: People will have preferences about how to arrange furniture during different phases of an event, and these **arrangements preferences** will converge spatially across participants.

RQ2: What UI control abstraction is best suited for the task of arranging robot furniture?

- H3: Participants will rate the interface as at least **moderately usable**.
- H4: Participants will prefer using higher-abstraction commands (select arrangement) relative to lower abstraction commands (set goal position) such that they will have **higher usability ratings** and **be used more** .
- H5: Participants using high-abstraction commands (select arrangement) relative to lower abstraction commands (set goal position) will perform better such that they will **complete arrangements faster** with **fewer collisions**.

Our results show that participants tended to create similar arrangements, finding our novel web-based control interface easy to use, supporting the viability of remote robot furniture arrangement as an application.

2 Related Work

Our study builds on past work on robotic furniture, multi-robot teleoperation, and UI design.

Robots and Furniture. Prior Human-Robot Interaction (HRI) research investigated the impact of furniture robots as actors in social environments. This included studies where robots offered services[14,19], nonverbally communicated needs[9] and invitations[1], as props in theatrical performances[18], and received help from bystanders[5]. Implemented morphologies included ottomans[14], drawers [11], trash barrels[19], chairs[1,9], walls[12], and adaptive modular joints[8]. Few works have evaluated the usability of robot furniture as we aim to[12].

Remote Teleoperation. Much work on remotely operating multiple robots has been conducted in various situations but few works directly relate to our multi-robot furniture application. Of this work, most focus on observational area coverage tasks (such as search and rescue[10]), or specialized niches (such as geriatric care[4]). We did not find any examples of tasks related to creating a multi-robot arrangement from an open-ended prompts (or other spacial multi-robot task allocation problem) that would be directly translatable to our work on multi-robot furniture.

User Interface Design and Evaluation. The design of an effective UI for a novel task is a difficult process for which tested frameworks, and methods of evaluation exist. Studies on mitigating detrimental human factors[3], and frameworks for designing robot UIs[17] are useful early in the design process. After an initial implementation, the UI can be evaluated by metrics related to user workload, and task-dependent performance[3]. Additionally, further optimizations can be discovered via human studies. For example, Roldán et al examined user input in various situations to detect "bottlenecks and inefficiencies" during a simulated multi-robot mission[13].

A significant design choice for human-robot systems is the level of abstraction at which interactions occur[3]. Levels of abstraction in multi-robot systems can span setting single-DOF low-level positional or torque commands, to commands involving the hundreds of DOFs in a swarm, coalition, or factory line. Increasing the level of UI abstraction for multi-robot system generally increases performance for many tasks by minimizing human bottlenecks. However, for open-ended tasks, higher levels of abstraction may impede the creative process which demands flexibility. As open-ended process, like furniture arrangement, are different than well-defined results-driven tasks, such as observational area coverage, the appropriate level of abstraction is an apparent gap in the literature.

3 Technology

Our implementation of **multi-robot furniture** involves three robotic chairs remotely tele-operable from a website. The ChairBot, originally designed by [9], consists of a wooden Ikea chair mounted on a Neato D3 vacuum. Three

ChairBots, an overhead camera tracking positions to localize the robots as they move in a control loop, and a web-based UI make up our multi-robot furniture system[1]. ChairBots planned paths greedily, independently, and were blind to obstacles such that they sometimes collided with eachother or their objects in their environment. The scene and web-based UI are shown in Figures 1, and 2 respectively.

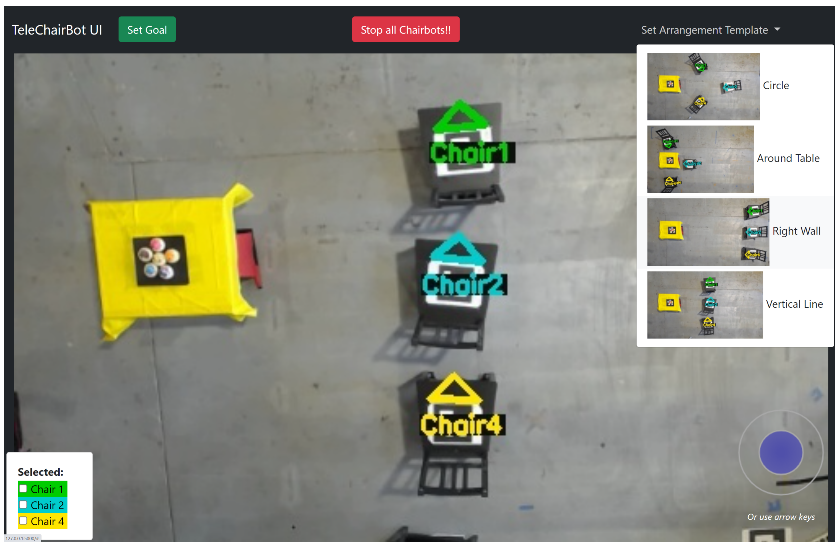

Fig. 2: The Tele-Chairbot UI with ChairBots in their starting positions. A live overhead video feed shows the room which includes the ChairBots and a non-robotic table with cupcakes. A joystick on the bottom-right can be used to send low-level motion commands. The top bar has the higher-level controls: set goal, and set arrangement template.

Prior work on our **ChairBots UI** had established the need for a screen-based controller, and some of its primary features for control[6]. These features include a remote interface, the ability to set and save arrangements, optimized positional and velocity precision, and the ability to move in a formation or adjust relative to room geometry. We build on the system and architecture by [16] by simplifying the web layout, extending image overlays, and adding a method to set individual ChairBot locations and orientations ("set goal").

4 Methods

This section describes our experimental manipulations, metrics, and procedure. A multi-robot system consisting of these ChairBots was chosen due to the impli-

[1] Code and build instructions available at `www.github.com/stoddabr/ros_flask`.

cation that robotized furniture is a multi-robot system and the fact that ChairBots have been previously studied in past HRI research[1,5,6,9]. A birthday party was chosen as the backdrop for this experiment as it is a realistic and relatable example of a multi-phase event, with similarities to larger-scale events[6].

4.1 Manipulations

Party Phase Prompts: The first manipulation we explored was prompting participants to create furniture arrangements for three phases of this birthday party. The three phases were handcrafted and chosen to represent distinct of a birthday party: “cutting **cake** at the table”, “watching a **magician** perform on the right side of the room”, and “a **dance** party on the floor”. Participants were told the party prompts as quoted. These activities were chosen as they offer a variety of social and behavioral considerations.

UI Type: A second set of manipulations aim to compare approaches for abstracting the control of a multi-robot furniture arrangement system and to determine their effectiveness. Users experienced two abstracted control modes: (1) **goal-based commands** in which users could move one chair at time with by clicking to set a waypoint location and orientation, and (2) **arrangement template**, in which a drop down menu of present arrangement graphics could be selected from. For both modes, we also provided a screen-based joystick for general fine-tuning. These were chosen as they represent multiple levels of abstraction: controlling robots with low-level motion commands with the joystick, specifying higher-level goals for individual robots, and, at the highest-level, giving goals for all robots. During the actual experiment, the first two trials participants experienced both of these conditions in a random order (balanced across participants). For the third and final trial they had the option of using either or both control modes.

4.2 Metrics and Measures

Five surveys, a semi-structured interview, and video recordings of the interaction were recorded for each participant. They included a **demographic** survey, a **post-trial** survey about self-perceived workload and performance, and a final **exit** survey containing the System Usability Scale (SUS) survey[2]. The post-trial survey included 7-point Likert scales from the NASA-TLX survey[7] which measure mental demand, and frustration level along with three custom questions about self-perceived success: ‘I was pleased with the final robot formation.”, “I was successful in performing this the arrangement task”, and “I was satisfied with my performance in this arrangement task”. The SUS Likert scale in the exit survey was adjusted to a 10-point scale to increase granularity[2].

The semi-structured interview consisted of 8 questions relating to performance, experience, and insights. These and improvisational follow-up questions were asked in an order determined by the Study Conductor based on the flow

[2] Adjusted cumulative score: SUS = 1.11 * [(odd questions - 1) + (10 - even questions)]

of the conversation. An example of the semi-structured interview can be seen at timestamp 31:35 of [15].

4.3 Study Procedure and Participant Instructions

Participants started by joining a Zoom call with a Study Conductor, which was recorded after consent was established (as per IRB-2020-0826). After the demographic survey, the participant was asked to role play as the employee of a company offering "robotic furniture arrangement as a service" wherein their job was to teleoperate robot furniture to meet the needs of a client.

The participant was then provided with a Tele-ChairBot UI web link url. The participants were initially trained in using the manual control method (see Section 3). Next, the participant was similarly trained on either goal or arrangement control. Once the participant was comfortable with the controls, they were **instructed to fulfill the client's Party Prompt exactly as quoted in Section 4.1**. They were then allowed to ask clarifying questions which, naturally, varied. No maximum time limit was set, however the participants were encouraged to not "keep the client waiting". Once the participant was satisfied with their arrangement or determined that no satisfactory arrangement was possible, the post-trial survey was administered (Section 4.2) before another trial was started.

Robotic failures occurring during the study were mitigated in one of two ways: the Study Conductor would attempt to fix the issue, or if the arrangement was close to complete, would physically move the ChairBot as indicated by the participant via the UI before the failure occurred. Failures required various amounts of time to recover from; the most common involved situations where the Neato batteries died requiring replacing or recharging (∼4 min), the Neato firmware froze requiring a reboot (∼2min), or the video server crashed requiring the user to refresh their webpage (∼5sec). Examples of robotic failures can be seen at timestamps 4:00, 14:45 and 18:27 in [15]. Upon completing all of the trials, an exit survey and semi-structured interview were conducted.

4.4 Participants

The study consisted of 3 trials within 12 participants (6 males, 6 females) of college age, resulting in 36 trials total for analysis. 10 of participants were recruited from outside of the robotics department and were unfamiliar with the research. On average, participants reported having a master's degree, higher than average levels of familiarity with robots, and were younger (all aged 18-35, $\mu \approx 23$) signifying a higher technical competency than average.

5 Results

This section presents the results of these experiments: (1) participant party phases prompts resulted in very similar arrangements for two of the three phases,

(2) both UI control modes were rated highly by participants, and (3) participants reacted positively to the UI.

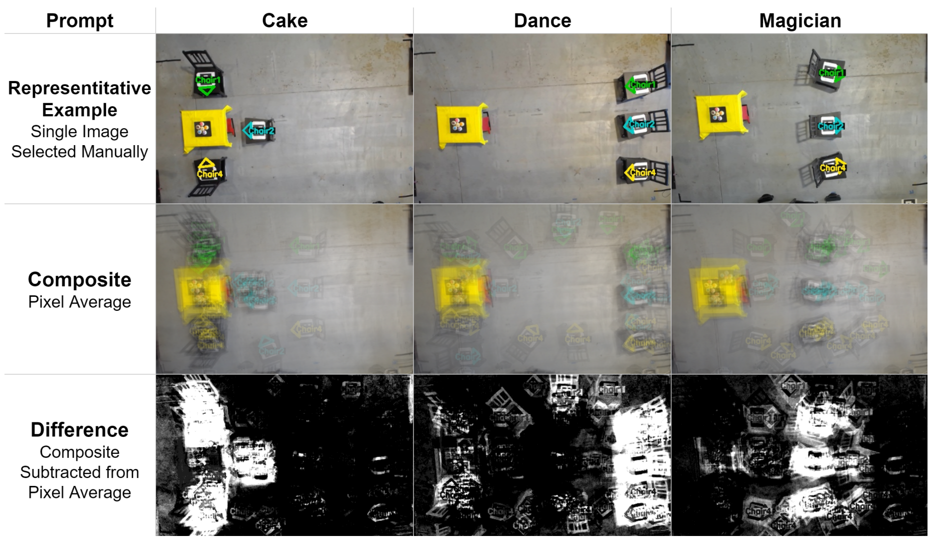

Fig. 3: Images in a table showing final arrangement information. The Representative Example was manually chosen to to show a typical/median arrangement. The Composite image was created from the mean of all arrangement images for that prompt. The Difference image shows the difference between the composite from an average of all arrangements in grayscale colorspace.

Participants Created Similar Arrangement Patterns by Phase. Several methods of composite image analysis were used to review combined final furniture arrangements for trials shown in Figure 3. To summarize, the cake phase contains a pattern of participants gathering the chairs around the table, with 10 of 12 participants clustered chairs around the table. For the magician performance, all but P03 arranged the chairs facing towards the right side of the room, where they were told the magician would be performing. The dance floor arrangements resulted in the largest variance: five placed chairs along the right wall, three placed chairs around the table, with the other participants exhibited more individualistic control arrangements that lacked emergent patterns. A commonality across the dance party arrangements was that the center of the room was left clear. No patterns were observed across UI Type.

No UI Control Modes Were Favored. Participants were exposed to two control modes (goal-based commands and arrangement template), however, neither UI control method was favored more than the other, failing to support H4. Upon completion of the trials, trial video footage was reviewed and the number of times each control method was used and for how long was collected, as shown in Figure 4, as was the final control mode used to position the chairs.

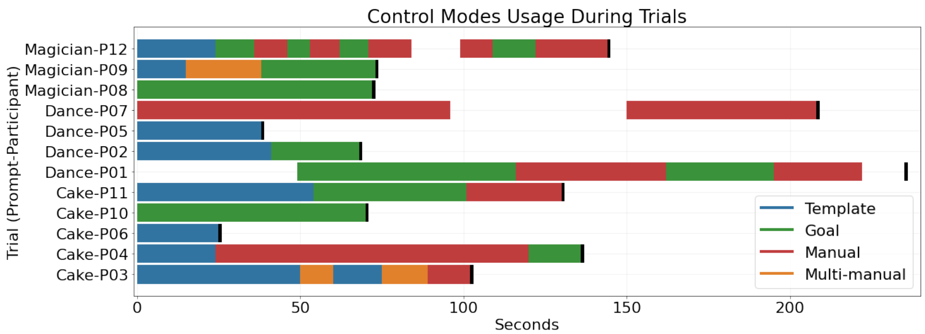

Fig. 4: UI control usage over time for trials in which participants could use all controls (UI Type=Both). Empty areas represent a participant thinking or otherwise not interacting with the UI. Moving multiple (2 or 3) robots at once was differentiated from moving a single robot manually. A black line denotes the end of that trial. Participants were given as much time as they needed for trials.

Only trials where participants were able to use all modalities (where UI Type = Both, i.e., the third experimental condition for all participants) were analyzed. Manual control was used 12 times, goal 12, template 9, and multi-manual 3. The average use time, in seconds, was 36 for manual, 34 for goal, 32 for template, and 16 for multi-manual. The qualitative data (Section 6) suggests that participants found differing utility for each UI control mode.

Data Source	Metric	Mean	Manipulation	P-Value	F-Score
Trial Survey	Self-Assessment of Success	6.1/7	UI Type	0.88	0.12
			Party Phase	0.63	0.46
	NASA-TLX Mental Demand	5.8/7	UI Type	0.69	0.37
			Party Phase	0.78	0.25
	NASA-TLX Frustration	5.7/7	UI Type	0.61	0.50
			Party Phase	0.93	0.064
Video Analysis	Time To Complete (seconds)	114	UI Type	0.95	0.042
			Party Phase	**0.060**	**3.0**
	Number of Collisions	0.30	UI Type	0.79	0.23
			Party Phase	0.28	1.3

Table 1: Mean value and results of an ANOVA tests run on trial-specific metrics and tested conditions. Statistically significant results are bolded ($p < 0.1$ and $F_{2,33} > 2.47$). For all survey questions, higher numbers are more positive.

Application and UI Experience were Rated Highly. Overall, our system was rated positively by participants across the SUS, NASA-TLX, and self-assessment questions. From our 12 responses, we arrived at a mean SUS score of $\mu = 75.1$ ($\sigma = 10.4$). Based on [2], this result is a "Good" level of usability, which supports H3. Interestingly, the first question of the SUS, “I think that I would like to use this robotic furniture system frequently”, was contentious with a wide distribution ($\mu = 5.4, \sigma = 3.0$). The NASA-TLX portion of the trial survey indicated that the tasks were considered simple and easy to complete with all participants reporting low absolute levels of stress as shown in Table 1. Self-assessment questions also resulted in high scores.

Across our two manipulations, there were no statistically significant results within the trial survey responses, shown in Table 1, nor between exit survey responses. This fails to support H4 as participants did not prefer using higher-abstraction controls.

6 Discussion

Participants were able to create satisfying furniture arrangements, supporting H1. Additionally all participants rating the system better than moderately usable. The resulting average SUS rating of 75 ($\sigma = 10$, “Good” as per [2]), and positively skewed survey scores support H3. However, the low number, and higher-than-average technical competency of recruited participants may be a confounding variable.

Party phase corresponded to furniture arrangement pattern, as illustrated in Figure 3 which supports H2. However, the amount of variability differed across prompts. The cake appears the most convergent (all but P03 placed ChairBots around the table), followed closely by the magician (all placed chairs in a central row facing right), with the dance prompt being more divergent (participants sporadically moved ChairBots towards the walls). One explanation for the cake and magician resulting in less variance than the dance prompt is the former suggest arrangement towards an object or place whereas the latter suggest an arrangement with furniture removed from an area. This suggests an axis for which furniture arrangement prompts may be described: spacial attraction around the prompt’s region of interest, whereby a positive attraction will result in less arrangement variability than a negative one.

Participants customize arrangements based on minute contextual criteria As different participants generated different assumptions, this supports and provides an explanation for H2: furniture arrangement preferences are heavily influenced by assumptions, about the use of the space based on available context. For example, P03 broke the trend of arranging the ChairBots around the table during the cake prompt saying they “assumed five people” were at the party based on the number of cupcakes on the table. There may also be cultural factors to take into account when for designing robotic furniture systems for different social or regional application domains.

7 Conclusion

In this work, we implemented a web-based multi-robot furniture teleoperation interface, running a remote study in which participants controlled robotic chairs over the internet. The study was designed to test a specific robot furniture application – making arrangements for multiple phases of a birthday party – and evaluated several control abstractions. This work offers support for the applicability of robot furniture arrangement as a useful domain for HRI research.

The results demonstrate that the participants were able to successfully create arrangement to accomplish a variety of tasks during a multi-phase event in the home, showing patterns in furniture arrangement across participants for well defined activities (cake, magician), as well as differentiation for more open-ended prompts (dance party). Though the goal control mode was the most popular, perhaps because of the balance of flexibility and ease-of-use, participants did not favor one control mode. For our study, UI Types did not significantly predict usability or performance, instead, usability rates were high across the board, indicating that multi-robot furniture UIs should be designed with controls over multiple levels of abstraction.

This work presents the first application-based use of robot furniture involving a remote operator rearranging furniture during a multi-phase event. Future work will seek to evaluate such a system co-operating in and around the people for whom the arrangements are meant to serve. Such results should also be tested on larger-scale, and heterogeneous systems to support more complex social settings such as conferences, classrooms, or social events.

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