AN ABSTRACT OF THE THESIS OF

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Abstract approved:

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Heather M. Knight

A chair, once placed, will stay put until moved. Or will it? With the rise of technology being embeddable into everyday objects, what if that chair could move itself? Such robotic furniture has been featured in advertisements, art, and Human-Robot Interaction (HRI) research. Existing methods for operating robotic furniture have been limited to commands at a low level of abstraction which limits the number of furniture robots usable at once as the operator becomes overwhelmed. This thesis explores how user interfaces can support the needs of human operators and interaction partners for arranging multi-robot furniture by iterating an interface for operating three chair robots (ChairBots) over two experiments. The first explores multi-robot furniture in a needfinding experiment to derive user-centric requirements. These requirements included a screen-based modality, autonomy, and geometric (i.e., spatial furniture-specific) intelligence. Requirements were met by implementing high-level affordances, and precise motion on the ChairBots. The second experiment extended the screen-based interface to enable tele-operation over the internet and refined affordances to three diverse levels of abstraction. This iteration of the interface was evaluated in a novelly remote user study wherein participants arranged the ChairBots in a simulated multi-phase event. Participants were able to arrange the ChairBots successfully proving the utility of a screen-based interface, and affordances at diverse levels of abstraction. Insights from this research can be used by future designers of multi-robot furniture and HRI researchers alike.

Designing and Evaluating a User Interface
for Multi-Robot Furniture

by
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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Brett Stoddard, Author

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CONTRIBUTION OF AUTHORS

Abrar Fallatah designed, helped run, and assisted in the analysis of the needfinding experiment presented in Chapter 4. Mark-Robin Giolando assisted with recruiting participants for and analyzing data from the evaluation experiment presented in Chapter 5.

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Chapter 1: Introduction

The world is seeing an increase in the use of machines that integrate human creativity, from robot comedy to human-in-the-loop robot delivery. Humans can input this creativity directly or indirectly; for example, a comedian prompting a robot to make a specific joke based on the audience's state [69], or operators of an "autonomous" delivery system tele-operating robots when they get stuck [29]. Technological systems can leverage human knowledge, perception, and ethics while operators benefit from the labor-saving attributes of the technology. To avoid bottlenecking human creativity, careful design of application-specific user interfaces is necessary; especially for robots that will operate near humans in shared, social environments like robotic furniture.

User interfaces for furniture robots are an interesting case study in the integration of human creativity due to furniture's omnipresent use by humanity, elevation to an art form (e.g., feng-shui), and utility. This utility extends from labor-saving commercial applications to Human-Robot Interaction (HRI) research where it is employed as a cost-efficient platform [34, 62, 63, 39, 4, 3, 71, 16, 18, 68]. Prior interfaces for multi-robot furniture in HRI consist of low-level direct drive controls. Increasing the number of robots makes direct low-level motion control unfeasible [31] which makes operating multi-robot furniture for HRI research or commercial applications infeasible. No higher-level command abstractions for efficiently operating a multi-robot furniture system had been developed prior to this thesis. This gap motivated an investigation into more efficient user interfaces for multi-robot furniture.

This thesis explores how user interfaces can support the needs of human operators for arranging multi-robot furniture via two main research investigations:

1. **Multi-Robot Furniture Needfinding Experiment Identified Features for A Screen-Based User Interface**

- First, we *analyzed* the data from a human experiment to derive features for a screen-based interface to control robotic furniture, identifying user desires for modality, autonomous motion, geometric intelligence, and positional precision.
- Next, we *implemented* a screen-based interface, which included affordances to autonomously command arrangements, move in formation, snap to gridlines, and move ChairBots at variable speeds.

2. **Application-Specific Evaluation of User Interface Shows Viability of Tele-operated Robotic Furniture Rearrangement**

    - First, we *extended* the screen-based interface to enable fully remote teleoperation over the web, adding three levels of command abstraction: preset arrangements, goal setting, and direct control.
    - Next, we *evaluated* this system with participants acting as remote operators of a robotic furniture system, who reported that the system was easy to use and appreciated diverse command affordances.

Chapter 2 summarizes related research relevant to our application: implementations of robotic furniture, common methods for designing user interfaces for robots, and a summary of human factors in multi-robot user interfaces. Prior work on robotic furniture in HRI establishes the motivation for this project as well as the state of the art in robotic furniture. User interface design for robotic systems, especially multi-robot systems, is difficult[1] Effectively designing a robotic system requires a deep understanding of the application and robot system refined over multiple iterations based on qualitative and quantitative user feedback data. Systems consisting of multiple robots require specific considerations such as efficient command abstractions to avoid hitting the limits of human cognition. These prior influential designs, research, and methods provide the basis for this thesis.

[1]General user interface design is NP-hard [49]; the inherent sensor noise, algorithms, and real-world environments of robotic systems contribute additional complexity.

Chapter 3 presents background on the ChairBot platform's initial state which was used and improved in this thesis: an economic, multi-robot system with chair-based morphologies used in prior HRI research. Prior experiments in HRI research are summarized which highlight the utility of this platform and suggest future work possible if effective multi-robot interfaces were developed. Technical details of the initial ChairBot system are also presented, including previous user interfaces, hardware, and software. The initial state of the ChairBot system as well as its history in HRI research are necessary to frame our contributions which extended this platform's capabilities.

Chapter 4 details a needfinding experiment conducted to determine user-centric requirements for multi-robot furniture, which were then implemented on the initial ChairBot platform. Discovered user-centric requirements include a screen-based user interface, improved precision, application-appropriate command abstractions, and implementation-appropriate autonomy. Participants in this experiment were asked to arrange this furniture to set positions using either multiple nonrobotic chairs or ChairBots with physical buttons for low-level motion commands. Collected data included coding of exhibited arrangement behaviors, a usability survey, and a semi-structured interview where participants were asked to share thoughts on expectations for and potential applications of multi-robot furniture. Results showed participants exhibited a range of strategies to move the ChairBots, that the physical user interface did not scale well to operating multiple robots, and that users expected furniture robots to be embedded with autonomy and room-based (i.e., geometric) intelligence, and operable from a screen-based device.

A screen-based user interface was created that implemented features to meet the found user-centric requirements. Features include 1) a **screen-based** modality implemented as a website, 2) the ability to *save* the current furniture arrangement and, in the future, *set* a saved **arrangement template**, 3) the ability to move multiple ChairBots while maintaining a **formation**, 4) the ability to autonomously **snap** to angles/gridlines, and 5) the ability to send precise[2], **low-level motion**

[2]Specifically, more precise angular motion relative to the initial ChairBot platform.

commands. The resultant interface was built as a website served from a ROS node. This website included a video feed for feedback, affordances for the described features using buttons for the autonomy-enabled user abstractions (i.e., features 2-4), and a virtual joystick for low-level motion commands (feature 5) [65]. This interface proved promising based on pilots, but required further validation to test that a) a screen-based interface was appropriate for multi-robot furniture arrangement, and b) the effectiveness of described features.

Chapter 5 details the extension of this screen-based interface to enable a novelly remote evaluation experiment seeing ChairBots tele-operated for a realistic application, which found this modality robustly usable when multiple affordances at diverse command abstractions are present. The interface from Chapter 4 was extended to enable tele-operatin over the internet, restyled to work on any sized device, and refined to only include commands at three levels of abstraction: set goals (i.e., waypoint control), arrangement template (as developed post needfinding experiment), and low-level motion with a joystick. These three levels of abstraction were identified and included to explore the usefulness of different abstractions in multi-robot furniture applications. The novelly remote nature of this experiment was both motivated and necessitated by the COVID-19 pandemic.

Remote participants, from the safety of their own homes, were successfully able to use this interface to move ChairBots based on open-ended prompts for a multiphase event which supports this modality for operating multi-robot furniture. The results of this experiment support our remote, screen-based modality and led to refined suggestions for operating multi-robot furniture. The ability for participants to operate the system in all trials across all manipulations suggests that remote tele-operation of multi-robot furniture is a well-poised modality. Additionally, no difference between performance or survey metrics across the different user interfaces implying that, for the number of robots tested, these two affordances are redundant.

Chapter 6 synthesizes the research contributions of Chapters 4 and 5 to further user interfaces for multi-robot furniture within the larger field of HRI. The user-centric technology requirements discovered in the needfinding experiment and then evaluated with promising results frame features useful for future implementations of multi-robot furniture. Qualitative data from both experiments suggest how multi-robot furniture can serve humanity and what is required for user interfaces to enable those applications. Several novel command abstractions were invented based on these applications and user-centric requirements in Chapter 4 that can be used in future implementations of multi-robot furniture. Additionally, the evaluation experiment results suggest that an interface seeking to enable creative tasks must include affordances enabling both high and low levels of control. The novelly remote method used in the evaluation experiment used can be replicated by future researchers to overcome challenges around recruiting participants to interact with real robots from a distance in real-time. Overall, we demonstrate how a user interface can enable remote operators to effectively create multi-robot furniture arrangements.

Chapter 7 concludes with a summary of the research conducted over the needfinding and evaluation experiments, contributions, and opportunities for future work.

Chapter 2: Related Research

Previous research on robotic furniture, user interface design fundamentals for robots, and human factors regarding multi-robot systems are foundational to our research on multi-robot furniture user interfaces. The intersection of these three areas provided useful information that was synthesized and built upon leading to this work's contributions in designing effective user interfaces for controlling multi-robot furniture.

2.1 PRIOR ROBOTIC FURNITURE

Prior implementations of robotic furniture provide inspiration and motivating applications for improving their user interfaces. This section overviews prior robotic furniture implementations spanning art exhibits, HRI research, and commercial applications. Both art exhibits and HRI studies leverage furniture as a morphology that is generally inexpensive, and immediately recognizable. Whereas, commercial applications seek to reduce human labor through the robotification of furniture.

Art exhibits utilize the familiar morphology of furniture along with the animated motion of robots to challenge cultural norms or express ideas. A good example of this is D'Andrea's robotic chair which cyclically and dramatically destroys and repairs itself. The cyclical nature of the chair's actions illustrates a Sisyphean struggle meant to inspire comparisons to our daily tasks that may seem equally meaningless to an outside observer [14, 22]. In the commercial sector, Nissan leveraged a self-parking chair prototype to market the technology for its self-parking cars [6]. The familiar nature of furniture in these examples acts as a backdrop and helps to focus viewers' attention toward the ideas being expressed by the artist, or marketing team, and away from the novelty of such a robotic system.

Robotic furniture has been leveraged by prior Human-Robot Interaction (HRI) research as an inexpensive platform for prototypical social interaction. Earlier research by Sirkin and Ju [62] established robotic furniture as an experimental design tool for HRI researchers. This research typically involved a recruited participant interacting with a perceivably autonomous robot secretly controlled by a hidden human operator, i.e., a *Wizard-of-Oz* (WoZ), to test the perception of autonomous robots without having to invest in its development [43]. A furniture modality for robots in HRI research is often employed for its low cost, and familiar morphology, which prevents biases that occur in some forms like humanoids [9]. Publications on these single robot systems attempt to optimize, or even detail, the operator's interface. Multi-robot WoZ work is limited by the ability of an operator to control complex robots [51]. As these robots get more complex, features of the operator interface and how it interfaces with autonomous capabilities will warrant more attention as is the case for multi-robot systems in other applications.

The success of single furniture robots in HRI has motivated extensions to the emerging field of mixed robot-human group interaction; however, operator bottlenecks currently limit the usable number of robots. As the number of robots increases the operator's workload increases proportionally up to a cognitive limit unless abstractions that leverage automation are effectively implemented into the user interface [41]. For furniture robots in social spaces, this cognitive limit is reached with relatively few robots (approximately 2) [19]. The study of user interfaces stands to further the understanding of multi-robot user interfaces by examining which methods were most effective in improving the interface such that those can be used in future multi-robot systems. Researching methods to improve user interfaces for one task may lead to innovations in other areas as multi-robot operators face similar problems across task domains. For example, robots that can autonomously move to a goal location set by an operator have been useful for many multi-robot tasks from search-and-rescue to delivery so improvements in autonomy or affordances, like a design enables an operator to set goals more effectively by not having to specify which robot will move to the goal [73]. Additionally, being able to effectively operate multi-robot furniture will enable multi-robot social interaction research which is an emerging area within HRI [59]. The desire to improve user interfaces for multi-robot furniture for the end user, and research applications motivated the work described in this thesis.

Another motivation for improving robotic furniture is its utility in **commercial applications** where it has been studied to improve aesthetics, reduce labor, or increase accessibility. Robots that can move furniture [56, 64] and robots for assembling furniture [37] have both been explored for their labor-saving potential. Similarly, motile (self-moving) robotic furniture, as explored in this thesis, has the potential greatly reduce the human labor required for the task of arranging furniture anywhere the same space is used for multiple activities. Today, event organizers and planners spent significant time and energy relocating furniture between different activities such as keynotes, workshops, or meals during a conference; multi-robot furniture can enable these transitions at the touch of a button. On the International Space Station, astronauts transitioning between work and recreation can command furniture from a laboratory environment to an entertainment center which may facilitate improved relaxation through the physiological benefits of a simulated *doorway effect*. Today modern robotics can enable such motile furniture, but what properties will meet commercial requirements (i.e., achieve product-market fit and widespread adoption) remains an open question.

2.2 METHODS TO DESIGN ROBOT USER INTERFACES

Previous research in User-Centered Design (UCD), human factors in tele-operated robotics, and robot autonomy and abstractions that was foundational to our user interface design is summarized in this section. Additionally, the JASON ROV project is presented as an example for how this research can be applied for a specific application. The task of designing a user interface for a robotic system often involves multiple iterations wherein operator and task requirements are identified, a system is built, and that system is tested to determine updates to include in further iterations. At each iteration, the refinement of designs requires careful considerations of appropriate features such as affordances, visualizations, and abstractions enabled by autonomy.

The ChairBots project adopts a UCD approach in which end users are active agents within the iterative design process [25, 55]. Along with the empirical assessment of effectiveness, end users' involvement is required to develop an understanding of their needs on the task at hand. End users evaluate working prototypes in an iterative process, such that each evaluation informs the redesign of the next prototype and user requirements in a continuous cycle [45]. The adaptation of UCD in HRI has been shown to improve both experience and performance across a range of robotics applications, including but not limited to domestic, service and social robots [45, 44, 5]. This work demonstrates the use of UCD in HRI by gathering ideas, observing behaviors, and collecting requirements to iteratively evaluate and design the robotic platform, especially user interfaces.

Previous implementations of and research in UCD on interfaces can bootstrap the design of similar robots in the future. Therefore, novel robotic systems offer useful contributions in the form of actionable **intermediate-level knowledge** [30]. User interfaces for operating multiple robots with furniture morphologies arranging based on human requirements is an example of such a novel application that no other known works have analyzed in-depth (as far as we are aware).

User interfaces can be described in terms of affordances (i.e., user inputs), visualizations (i.e., information output for the user), and, for intelligent systems, autonomy. The model used to describe user interfaces is shown in Figure 2.1 with examples of how it applies to specific commands shown in Appendix D. The term **affordances** in Human Computer Interaction (HCI) [1] researchers and designers to describe functionality that is, ideally, self-descriptive in its function. Good affordances lead to systems that are easily used with little to no training such as a large red button on a robot with the words "Emergency Stop" to immediately kill power to the system. **Visualizations** is another term borrowed from HCI that

[1]The term affordance was initially invented by biology to describe the mechanism of animal perception and decision making [24] but the HCI definition by Norman is used in this work [47]. Many other fields leverage affordances with different connotations: psychology, ethnography, philosophy, healthcare, and robotic manipulation.

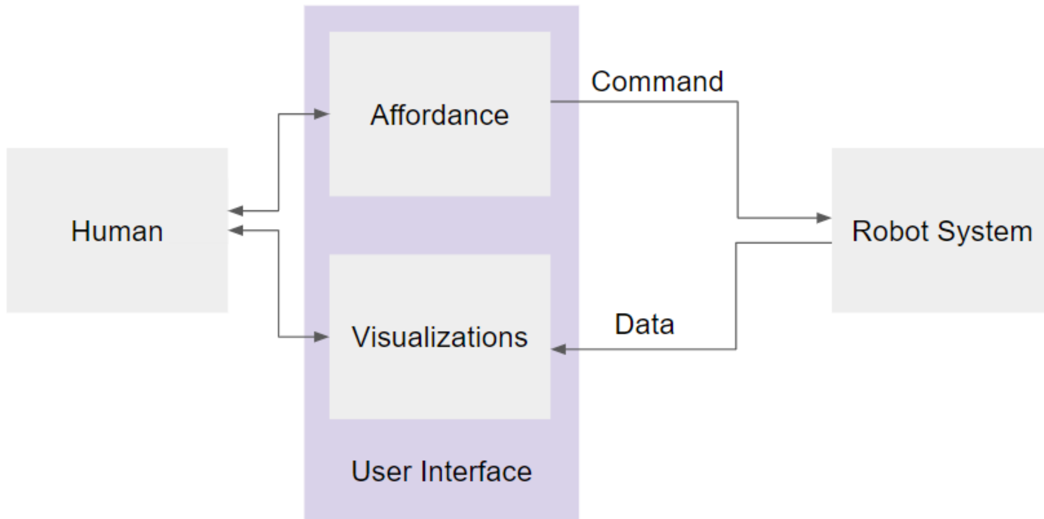


Figure 2.1: Abstract model of a user interface used to control a robot system. Commands are sent from a human via affordances on the user interface, which impacts how the robot system senses, thinks or acts. Data from the robot system is passed to the human in the form of visualizations (ranging from charts [70], multi-modal feedback [67], to even expressive robotic motion [38]). Arrows between the human and interface are bidirectional to represent that affordances may involve multiple steps and visualizations may be intractable. This model is based on a synthesis of models by Norman [47] and Szafir and Szafir [70].

involves the representation of information in forms easily interpreted by humans. This often takes the form of visually mapping digital information onto spacial displays such as graphs, maps, or reconstructed digital environments. Visualizations in robotic systems provide situational awareness to an operator such that they can make informed decisions [70].

An **autonomous** system is one with agency such that it can take actions on its own accord via an algorithm from stored or sensed information. Autonomous robots today span in complexity from mousetraps (which mechanically "perceives" a mouse and is programmable by adjusting the sensitivity) to multi-robot swarms of drones offering consumers on-demand roof inspections [7]. Robots exist in the physical world, collect lots of data through their sensors, and make autonomous decisions; factors that impact the design of their user interfaces. Careful design of appropriate abstractions in these interfaces is vital to establish situational awareness for the user and effective operation by the user [70].

Establishing situational awareness and enabling effective control for tele-operated robots is challenging yet vital as illustrated in the JASON ROV project. Unlike many other types of interfaces, tele-operation implies that the operator is outside of the robot's environment meaning that all situational awareness must be presented by the interface. Foundational work on this modality was developed by Sayers for the underwater JASON underwater robot used by the Woods Hole Oceanographic Institution [57]. Sayers's system involved an operator using an interface to view a display and send commands to JASON which will, with some local autonomy, execute the commands. To maximize the information gained through this display, virtual fixtures were integrated which involve introducing artificial perceptual information onto data streams [53]. For example, overlays on a video feed showing information about a robot's workspace, or repulsive haptic forces on a controller activating to avoid an anticipated collision [58]. As data is propagated across a network to the human, delays build up into noticeable latency any of which impacts control systems, and operator perception. This latency along with maximum bandwidth limitations creates information bottlenecks the designers of robot user interface must work around. More recent surveys on the challenges of robotic teleoperation show how the issues of situational awareness, latency, and effective autonomy persist in interfaces today [12, 48].

The design of affordances and visualizations requires care when considering robotic systems with significant autonomous capability as the nature of interactions changes from direct control to interfacing with an agent. Systems with autonomy can be operated on at a higher **level of abstraction** such that an agent is given responsibility for **observing** a subset of the situation the human would otherwise be required to watch and act on [20]. How affordances and visualizations are designed to appropriately address this higher level of abstraction depends on the application and robot capabilities. Typically, commands at higher levels of abstractions are presented in a screen-based interface [67]. Ontology frameworks for describing this have been proposed from both the perspective of the robot's autonomy, like Beer's framework with a 10-point scale [10]), and from the perspective of the human's abstraction, like the Levels of Human Control Abstraction (LHCA) [33]. In the spirit of being human-centric, the LHCA is used in this work to describe autonomy.

2.3 FACTORS IN MULTI-ROBOT USER INTERFACES

This section briefly summarizes models, methods, and current state-of-the-art research that seeks to enable a single operator to effectively operate multiple robots. No robotic systems today are fully autonomous: even the most capable require a human to press the "on" button to start a mission and the "off" button when they complete their task (or ~~if~~ when autonomy fails).

A human's cognitive abilities often limit the performance of a system when they are asked to operate multiple robots [31]. One way to predict the maximum number of robots that can be operated before this ceiling is to calculate the *Fan-Out* (FO) metric:

$$FO = \frac{NT}{IT} + 1$$

Where NT is the *Neglect Time* or expected between required operator interventions before that robot's performance drops, and IT is the *Interaction Time* or expected time for each intervention. Although experimentally inaccurate, this models the fundamental relationship that a user interface for a multi-robot system can be improved by either increasing the effectiveness of autonomy (i.e., $\uparrow$ NT) or improving the efficiency of sending robot commands in the user interface (i.e., $\downarrow$ IT).

User interfaces can be improved through innovations in affordances, visualizations, or command abstractions (as discussed in Section 2.2). Looking at two surveys on user interfaces for multi-robot systems, it can be seen that the most common command abstraction is waypoint control with 14 out of 24 [31], and 5 out of 9 [72] multi-robot control publications utilizing it. Typically, waypoints involve the operator specifying a goal position for a robot which the robot then autonomously approaches. Waypoints as a command abstraction can be enabled with simple affordances such as clicking a spot on a map that visualizes task-specific data (e.g., heatmaps showing danger or points of reference). With command abstractions like waypoints, a human can effectively operate around 4-8 robots

For more autonomous multi-robot systems, the limitations predicted by the fan-out model can be broken by leveraging affordances that send commands to multiple robots at once. These include such interactions as plays in the playbook, which are preset commands corresponding to multiple joint operations [46], or swarm-level commands, like controlling a swarm leader [50]. According to [31], "humans were able to control hundreds [of robots]" using interfaces with commands at a higher level of abstraction. Similarly, visualizations at higher levels of abstractions have been shown to enable human operators to effectively control robotic swarms in the hundreds [54]. Examples of multi-robot systems further illustrate how higher levels of abstractions can improve the efficiency of multi-robot systems, but other times inhibit control.

User interfaces for operating fleets of Autonomous Underwater Vehicles (AUVs) during scientific expeditions provide reality-tested examples of how affordances, visualizations, and autonomy come together for multi-robot user interfaces. Two examples of user interfaces for AUVs are the Neptus [15] and WiMUST [61] mission planners. These are used to plan out and monitor ongoing surveillance missions wherein AUVs collect environmental data around a designated area. During ongoing missions, they contain two data visualizations: spacial information related to the mission, and data about the robot's estimated past, current, and planned states. Affordances exist to change planned states (often using waypoints) if deemed necessary based on this data with autonomy operating. Szafir and Szafir provide an example of how even such well-used interfaces can be improved by identifying and designing around the operator's *data tasks* [70]. Due to the nature of

AUVs, this setup enables an operator to effectively control several robots for weeks at a time [61]. As AUVs are used for objective area coverage tasks higher levels of control lead to efficient operation even with many robots over large time scales.

Other tasks require human creativity to reach goals such as underwater manipulation tasks. In contrast to observation, autonomy often fails at the task of underwater manipulation as the Ocean is an extremely energetic environment and contact physics underwater are difficult to model. When these failures occur, they often require a human's creative input to recover due to the difficult nature of underwater manipulation. For example, during a mission, Ocean One, a semi-autonomous humanoid ROV, got stuck on some debris while attempting to surface which required a human operator to take over full control and carefully dislodge the robot over an extended amount of time compensating for periodic currents and floating debris [11, 36]. Although underwater manipulation tasks are objective, their reliance on low-level human operator input shows how human creativity is required for recovering from failures.

Truly creative tasks in the field of multi-robot HRI are relatively rare, but previous research on theater robots illustrates how lower levels of control are required to avoid frustrating users. This bias is illustrated in how every paper reviewed by both [31] and [72] is limited to objective "area coverage" tasks like observation or search-and-rescue. The theater provides a stage shared by both humans and robots for facilitating entertaining creative expression. User interfaces for operating multiple theater robots on stage appear to be limited to low-level direct control either by someone on-stage [71, 16] or from behind the curtain [32]. Similarly, previous research on robot comedy developed low-level interfaces to branch jokes [69]. This is assumably due to control at a higher level of abstraction creating restrictions for how the operator (now artist) can express themselves. As also shown in Chapter 5, when designing user interfaces for creative tasks it is important to include affordances at lower levels of abstraction that are less likely to bottleneck or prevent creative actions.

Chapter 3: ChairBots Background: History and Technology

ChairBots have been used by our lab as an economical platform for HRI research and served as the entry point to multi-robot furniture user interfaces for this thesis. The ChairBot platform consists of chairs with motors that can be safely sat on as illustrated in Figure 3.1. Its evolution over the years in various experiments is detailed in this chapter along with a technical description of the hardware, software, and user interfaces before they were expanded as described in Chapters 4 and 5.

3.1 USE IN HRI RESEARCH

The **ChairBots** was originally established by Knight et al. as a cost-effective platform to research the use of expressive motions and non-verbal behaviors to communicate robots' intentions and evoke human responses in social spaces [39, 2]. Knight et al. built the social ChairBots and detailed its hardware and software subparts, then followed the work with improvisation session to design the communicative motions[39, 4]. Knight et al. examined the ChairBots' behaviors empirically in and outside the lab using the Wizard of Oz techniques, where participants engaged with robots that appear to be autonomous [39][2].

Other work introduced a physical interface on the ChairBots such that co-located humans can move the robots as if they were interacting with wheeled chairs [71, 16]. Sending commands to multiple ChairBots at once was tried but were not used in any experiments as they either required a large number of buttons, complicated multi-touch interactions both which were difficult to remember, or prohibitively expensive hardware.

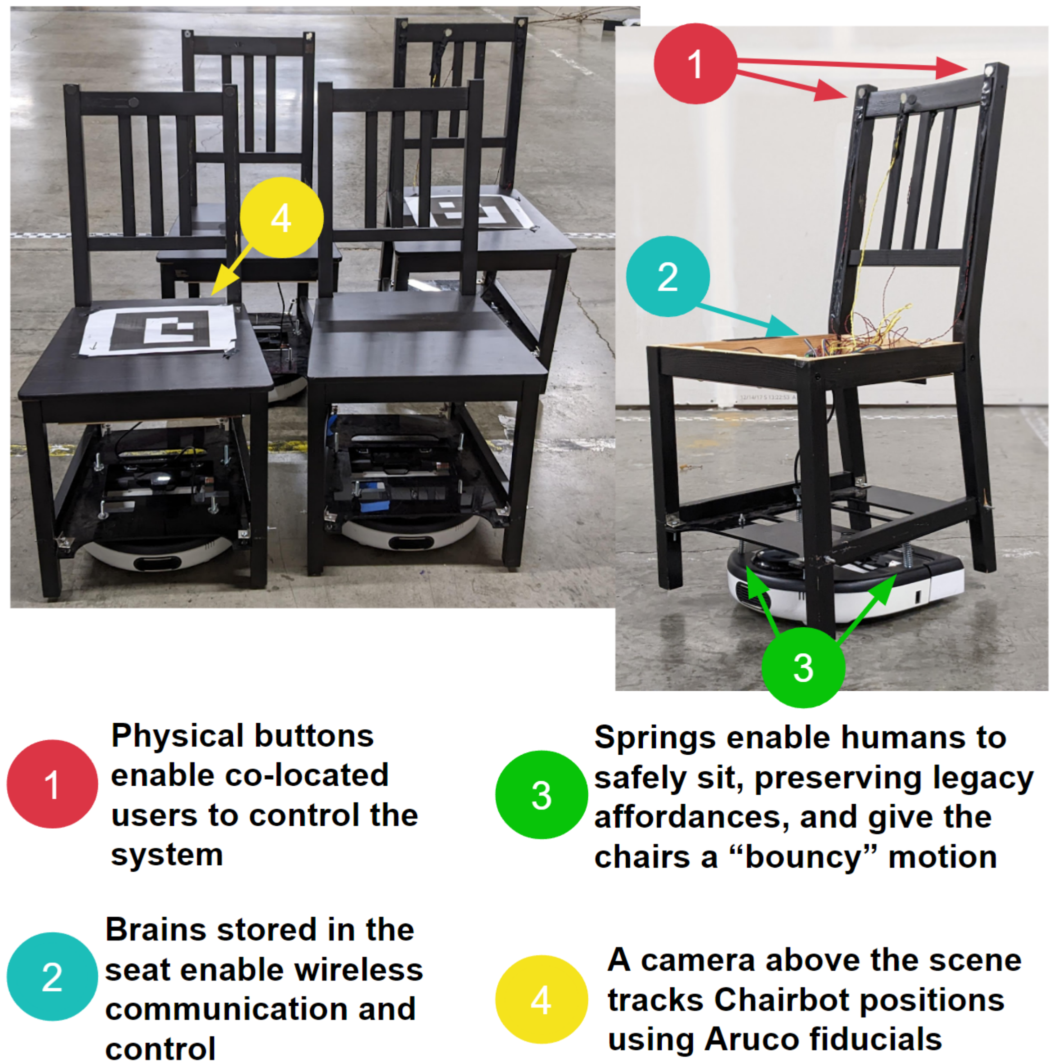


Figure 3.1: Description of the ChairBot robot with major features highlighted and explained.

3.2 TECHNOLOGY AND SPECIFICATIONS

The original ChairBots system including hardware, software, and the user interfaces used in prior HRI studies is described here. During this work, only the user interface and communication software were updated with the hardware largely remaining constant.

3.2.1 Hardware

ChairBot hardware consists of a chair backbone, motors that enable motility (self-powered motion), a server enabling centralized command and control, and, depending on the experiment, an external camera. The chair of choice was an Ikea Stefan model which, when purchased, retailed for $20. Motors consisted of a Neato D3 robot vacuum which was hacked with a Raspberry Pi to accept direction commands from a ROS topic sent from the centralized ROS node running on a laptop.

The optional camera provides important localization feedback information using AruCo fiducial markers, which were leveraged for implementing autonomous motion as described in Section 4.4, as well as providing information to the user. For experiments that required the operator to be remote, such as WoZ experiments, a video feed is the only source of situational awareness. This camera angle also provided a useful data source for experiments as it captured objective location information useful for proxemics [1, 4], the motion analysis in Chapter 4, and recording final furniture arrangements in Chapter 5. For the sake of this thesis, this camera was placed overhead the scene in which robots moved as shown in Figure 3.2.

3.2.2 Software and Networking

The Robot Operating System (ROS) was leveraged as a framework for both organizing the software necessary for controlling the ChairBots and networking to wirelessly communicate with them. This was originally used to enable a remote

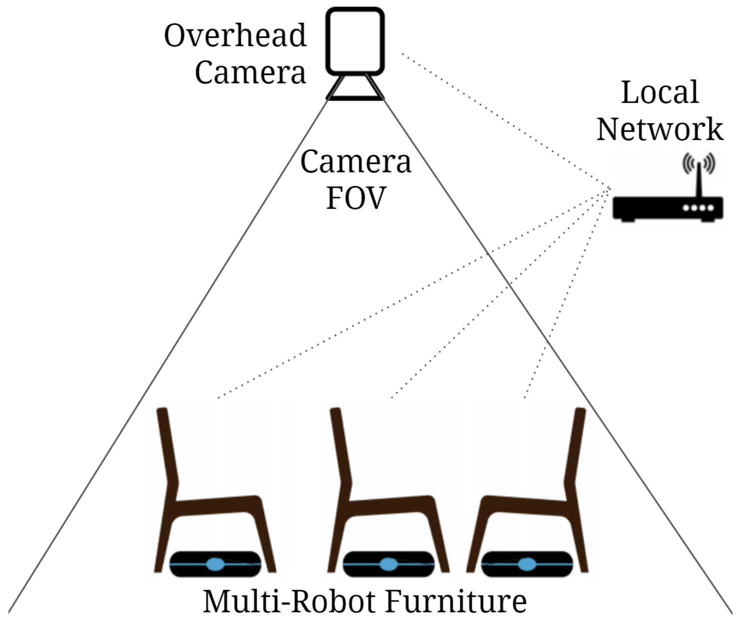


Figure 3.2: Side view of the scene in the lab with the overhead camera and wireless networking connectivity shown relative to the ChairBots.

operator to control a single ChairBot but was flexible enough to enable multiple robots to be used each with their own topics. The publisher/subscriber pattern was employed to send motion commands to ChairBots from the central server[21]. ROS requires all robots to be on the same wireless network as a central *master* node, or across different networks which have port forwarding enabled [27].

3.2.3 User Interfaces

The user interface on the ChairBots consisted of low-level motion commands sent from either physical buttons, a game controller, or a website. All controllers sent only low-level motion commands: forward, backward, or turn. Originally, linear commands were set to a constant speed which was later augmented with variable speeds in Chapter 5. Similarly, angular commands originally enabled a precision of ± 5 deg which was determined in Chapter 4 to be noticeably imprecise for human

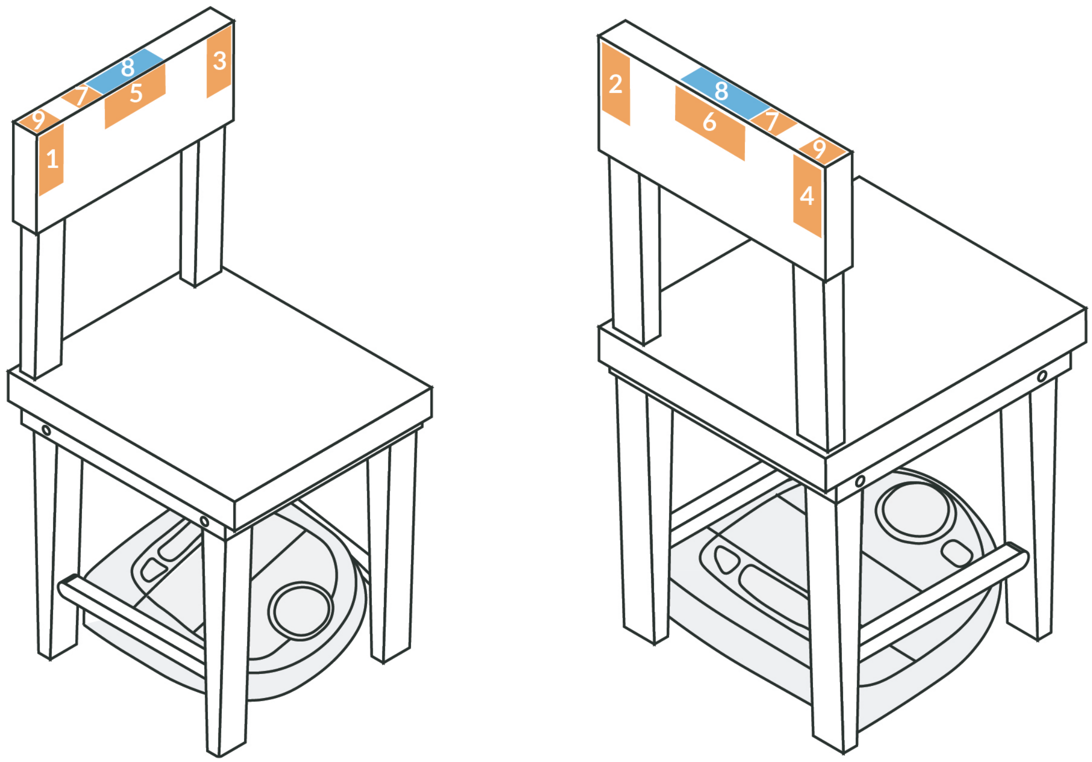


Figure 3.3: Schematic diagram of a ChairBot with 6 adhered touch sensors. **1,2:** Turn Left, **3,4:** Turn Right, **5:** Go Backward, **6:** Go Forward, **7:** Turn the robot On/Off, **8:** LED indicator, and 9: Turn All robots On/Off

perception of furniture arrangement and so higher granularity angles were enabled at ± 1 deg.

Physical buttons on the ChairBots provided an interface for co-located humans to move the robots used in previous research [71, 16]. This was inspired by the legacy affordance of pushing chairs with the benefit of a reduction in mechanical efforts required by the user. The mapping of these buttons to commands is shown in Figure 3.3. These buttons were used as a prototypical interface during the Chapter 4 needfinding experiment. Sending commands to multiple ChairBots at once was attempted in some unpublished pilots but was never fully implemented. Such complex, higher abstraction commands require lots of buttons, or complicated

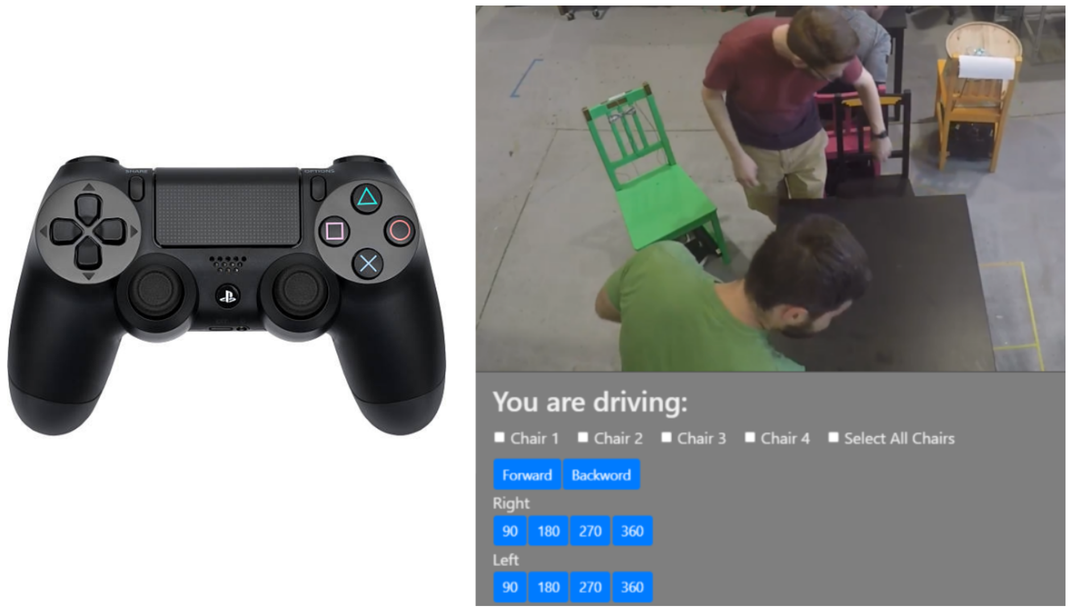


Figure 3.4: Images of the remote interfaces on the original ChairBot. **Left:** a PS4 controller where joysticks mapped to low-level motion commands. **Right:** a website with embedded video feed with affordances to move the ChairBot linearly or turn in place at an increment of 45 deg.

multi-button interactions, both of which are difficult to teach and remember.

For prior research where the user was remote, a simple website or game controller interface was used [39, 2]. Both consisted of affordances for low-level directional commands. The website had a video feed from the camera embedded in it and buttons to move the ChairBot as shown in Figure 3.4. This simple website was forked to bootstrap the development of the screen-based interfaces described in Chapters 4 and 5.

Chapter 4: Understanding Human Needs for Arranging Multi-Robot Furniture

This chapter presents human expectations for controlling robotic furniture by 1) analyzing the results of a needfinding experiment to derive user-centric technical requirements, and 2) describing how these features were incorporated into a screen-based user interface for the ChairBots platform[1]. The resulting technology was a user-centric screen-based interface for motile, multi-robot furniture control.

4.1 INTRODUCTION

Event organizers and planners spend a lot of time and energy setting up and relocating chairs according to sequences of events; on-going activities are sometimes delayed during an event due to this manual rearrangement. Event guests are sometimes supposed to move from one room to another for upcoming activities (e.g., from a lecture formation to a reception formation in a conference). As such, chair arrangement is labor-intensive and time-consuming, especially in hosting and participating in large-scale events such as conferences and receptions.

Robotic chairs that automatically relocate can reduce the time and the energy associated with organizing social events, if the system adequately meets people's expectations and have a functional user interface. Existing studies on robotic furniture demonstrate its utility as a tool [4, 71, 17, 19] and a social actor with its ability to interact with people in shared spaces during collaborative arrangements [2, 63]. Additional demonstrations of robotic chairs have demonstrated the feasibility of commanding many chairs at once [23]. We explore the user interface requirements of multi-robot furniture behaviors. We present the work in two

[1] This work was published in both [19], as a paper at the International Conference of Social Robotics (ICSR), and [65], in a demonstration video at ACM/IEEE International Conference on Human-Robot Interaction (HRI), by Abrar Fallatah, myself, and Heather Knight.

Figure 4.1: This paper presents an empirical needfinding experiment and the resulting technology improvements based on participants' ratings and perspectives. The figure features the robotics chairs and the mobile tele-operation interface for controlling them.

phases: (1) a needfinding experiment, and (2) technology improvements of the interface and control system.

Specifically, this was structured to answer three research questions:

1. Where do people want robot chairs?

2. What do people think of the ChairBot?

3. What are the controlling methods, range of arranging behaviors, and technical requirements of automated robotic furniture?

In the needfinding experiment, participants were recruited to interact with a prototypical physical interface to arrange both robotic and non-robotic furniture and ideate on futuristic aspirational systems with a focus on usability. From videos and surveys, data about participant impressions, desires, use-cases, and arrangement behaviors were determined. Results from this experiment were analyzed to derived desired technical requirements including a screen-based handheld modality, autonomous motion, geometric intelligence, and greater positional precision. This feature set was implemented on the ChairBot system implemented as affordances which enabled a user to to autonomously move multiple ChairBots to **arrangement templates**, move multiple ChairBots in a **formation**, **snap** ChairBot orientations along gridlines, and low-level motion with a lower granularity.

Results contribute foundational insights for reliable multi-robot furniture systems to enable future human-robot interaction research utilizing robotic chairs. Furthermore, our insights into user expectations of robotic furniture rearrangement provide a backdrop to explore challenges in multi-robot/multi-human social interactions. When it comes to the cost-efficiency of HRI research in social robotics, the use of simple robot platforms is an excellent example of a low design effort.

4.2 NEEDFINDING EXPERIMENTAL METHODS

To understand the requirements of motile, robotic furniture, participants were recruited in a two phase experiment involving an interaction experiment with chairs, and an reflective interview. Participants were asked to arrange both robotic and non-robotic chairs in two types of arrangements in a mock room (either in an open space and/or around a table. Then, participants were interviewed about their experience following a semi-structured script.

12 participants were recruited across varying ages (18 - 35) and genders (six males, five females, and one non-conforming). Over two trials each participants was asked to move both chair versions, two one of two locations in the room shown in Figure 4.2. This experiment was lead by a researcher co-located in the space and data was collected through surveys and from analyzing videos.

4.2.1 Technology

This experiment asked participants to interact with both robotic and non-robotic chairs. The use of non-robotic chairs in this experiment presented a useful baseline for understanding how robotic furniture changes interactions with robotic counterparts. The robotic chair involved a version of the ChairBot described in Chapter 3 with only the physical button interface active. This button interface was used for two reasons: at the time, the screen based interface was more complicated to operate, and it was assumed that the physical interface is easier use based on our lab's prior research with the ChairBots (especially [16]). During the experiment, only one participant identified themselves as experienced with robots while the majority self-identified as novices on a 1-5 Likert scale (1=None and 5=Expert; M=2.58, SD=1.31).

Additionally, the same chair frame used for the ChairBot morphology (the Ikea Stefan) was fitted with castors to make juxtapositional non-robotic chairs. The castors enabled the chairs to wheel-around with little effort which mirrored the effort required to push buttons on the ChairBots.

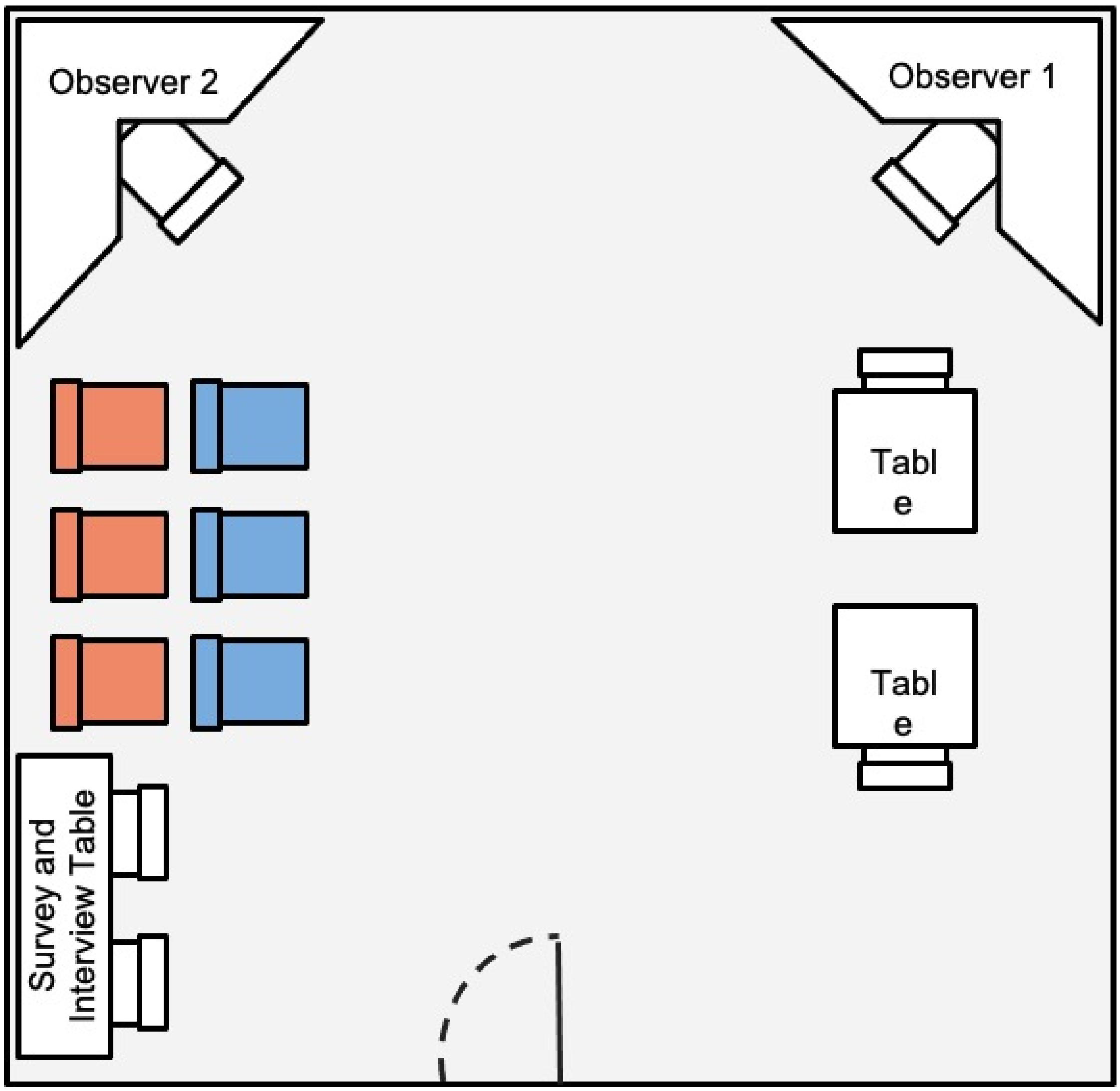


Figure 4.2: Overhead view of the experiment area, showing the starting position of both Non-Robotic and Robotic chairs. The tables participants arranged the chairs around are sketched to the right.

	Chair Type ***Counterbalanced For All Participants***	**Space Type** ***Counterbalanced For Every Group***
P1	(Robotic, Non-Robotic)	(Around Table, Around Table)
P12	(Non-Robotic, Robotic)	(Around Table, Around Table)
P9	(Robotic, Non-Robotic)	(Around Table, Around Table)
P8	(Non-Robotic, Robotic)	(Open Space,Open Space)
P11	(Robotic, Non-Robotic)	(Open Space,Open Space)
P10	(Non-Robotic, Robotic)	(Open Space,Open Space)
P2	(Non-Robotic, Robotic)	(Around Table,Open Space)
P7	(Robotic, Non-Robotic)	(Around Table,Open Space)
P6	(Non-Robotic, Robotic)	(Around Table,Open Space)
P3	(Robotic, Non-Robotic)	(Open Space,Around Table)
P4	(Non-Robotic, Robotic)	(Open Space,Around Table)
P5	(Robotic, Non-Robotic)	(Open Space,Around Table)

Table 4.1: All participants made one arrangements with non-robotic chair and one arrangement with robotic chairs. Chair type was within-subject (i.e., all participants experienced both chair types), and Space type was between-subject (i.e., half the participants experienced Open and half experienced Around).

4.2.2 Manipulations

Two independent variables were counterbalanced to understand the effect of robotic chairs across situations. The first independent variable was **Chair Type**, with robotic chairs being ChairBots and non-robotic chair type being the same model of chairs on wheeled casters (as described in Section 4.2.1). The pairings of participants to these variables were done such that participants interacted as shown in (Table. 4.1). The order in which a user interacted with Chair Types varied such that half interacted with the ChairBots first and the other with the non-robotic chairs.

The other independent variable, **Space Type**, dictated the space around which the participants arranged the chairs: two preset tables or an empty space. The tables are shown in Figure 4.2 with open space referring to the center of the room.

4.2.3 Metrics

Both explicit and implicit data was collected during the experiment and following interview. This data was collected from video-recordings of the experiment area using two cameras, with overhead and isometric views, and sound recordings. Explicit data also included a five-point Likert scale survey given after each trial asking participants to rate the non-robotic and robotic chairs on three desirable characteristics: mobility, usability, and enjoyability. This survey questions can be seen in Appendix A.2.

	Category	**Data Source**	**Data Type**	**Definition**
RQ1	Use-Cases	Interview Video	Verbalization	Situations in which robotics furniture can be used
	Contexts	Interview Video	Verbalization	Circumstances in which robotics furniture can be used
RQ2	Mobility	Questionnaire	Likert Scale	Average of scores based on how *expected, appropriate, and natural* the motions were as perceived by users
	Usability	Questionnaire	Likert Scale	Average of scores based on how *obvious, easy to use, and convenient* the robots were as perceived by users
	Enjoyability	Questionnaire	Likert Scale	Average of scores based on how *likeable, pleasant and simple* the robots were as perceived by users
RQ3	Controlling Methods	Interview	Verbalization	Modalities to control robotics furniture
	Arranging Styles	Video	Behavior	Strategies participants used to arrange the chairs
	Feature Requirements	Interview, Video, Questionnaire	Verbalization, Behavior, Free text	Features participants expressed the need for, used or thought about

Table 4.2: The 9 categories of data we collected as dependent variables, sorted by research question.

After the second trial survey was finished, additional explicit data was collected via a reflective interview with the participant. This semi-structured interview focused on participants' expectations of robotic furniture to prompt ideas about suitable implementations. These interview questions can be seen in Appendix A.1.

Qualitative data from the interview and experiment scripts were analyzed the data in three steps. First, we transcribed the data and broke it in the order of speaking (i.e., participant vs. researcher). Then, a team of two researchers coded 20% of the data independently. We selected this data randomly from 4 different participants. The two researchers reached an agreement of 98%. Given this reliability, one of the researchers coded the rest of the data as the last step. Finally, we stored the dependant variables and associated each one with a research question (Table.4.2), to conclude the work.

4.3 NEEDFINDING EXPERIMENT RESULTS

The results this experiment was analyzed in terms of a quantitative analysis of the manipulations effect on survey responses, a qualitative coding of arrangement behaviors exhibited during the experiment, and desired features of multi-robot furniture derived from transcript data from both the epxeriment and interview.

4.3.1 The Impact of the Experimental Variables

In this section we report on how the experimental variables – chair-type (robotic vs. non-robotic) and space-type (empty space vs. around table) – impacted participant's questionnaire ratings, exhibited behaviors, and feature suggestions.

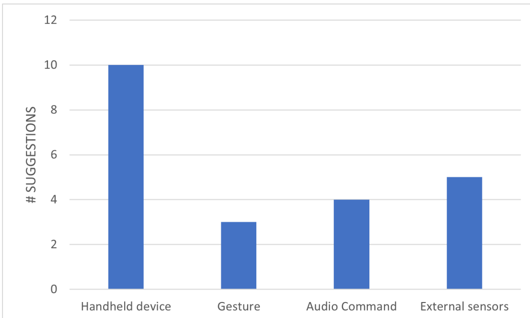
Survey responses: Overall participants ranked the non-robotic chairs higher in terms of mobility, usability, and enjoyability (Fig. 4.4a). The lowest ratings of the robotic chairs were for mobility and usability. For example, P7 stated, *"The non-robotic chairs felt natural to push and pull. The robots moved successfully but required a bit of patience."* On the other hand, in terms of the second research variable, participants ranked all types of chairs more highly in the constrained around-table space condition (Fig. 4.4b). Perhaps making an arrangement in an open space seemed like less of an achievement.

Use Cases and Contexts: When asked about future use cases and context, people had different preferences about what kind of furniture (robotic or normal) ought to be used in what domain. For example, participants suggested robotic chairs for dining, socializing, and the home at a higher rate than other categories (Fig. 4.4c). On the other hand, they preferred normal chairs for offices, schools, and meetings. We also coded for use-cases of other types of robotic furniture, which were most often mentioned in reference to utility or the home. For example, P9 said *"I have a fireplace, and then there's a piece of furniture like a metal basket that holds the firewood. That [metal basket firewood] robot would be pretty sweet, because then I wouldn't have to move the materials as far"*.

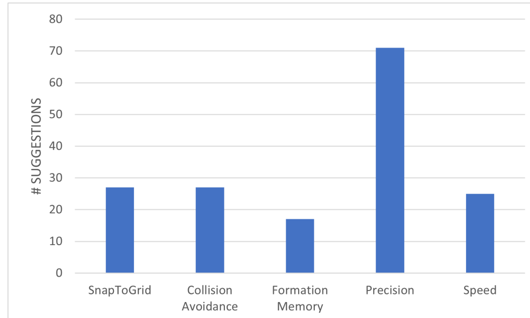
Arrangement Behaviors: A coding process of participant behavior resulted in four observations of participant arrangement behavior. Where some participants used several arrangement styles, others used a single style throughout. These styles are:

1. **Staging**: The participant moved several chairs closer to the final position.
2. **Sequential**: The participant moved chairs one-by-one at a time to the final position.
3. **Explorative**: The participant moved chairs to several positions before settling on a final position.
4. **Inquisitive**: The participant cleared other objects (i.e., tables, non-robotic/ robotic chairs) before attempting to move the chair.

Fig.4.4e displays the distribution of styles that participants used. The most used arrangement style was *One By One* and the lowest was *Clustering* regardless of the chair-type (non robotic vs robotic). All 12 participants used the One By One style for at least part of their trials, grabbing a chair and placing it at a desired location. Participants were more likely (58%) to use the Clear The Stage style (i.e., clear the space before making an arrangement) with robotic chairs, perhaps



(a) Suggestions for interface modality



(b) Suggestions for ChairBot features

Figure 4.3: Results from the empirical experiment. Suggested interface modality (e.g., "I wish I could control them with...") and low-level features (e.g., "I wish that ChairBots had...") based on grounded coding. Data is summed from both experiments and interview.

because they anticipated the mobility limitations of the robots. This data suggest that future robotic furniture systems allow for a range of participant setup styles.

4.3.2 User-Desired Features

Categories for user-desired or expected features were determined and quantified based on transcript data from participants while arranging chairs in the experiment and reflective interview. These included the desire for a mobile, screen-based user interface for operating the ChairBots, the expectation for the ChairBots to have some geometric knowledge about the space, and desire for higher precision motion commands while operating the ChairBots.

Desire for screen-based control interfaces: 84% user's surveyed suggested the use of a screen-based controller, for example, P5 asked "is there an app for this?". Additional control method requests (in descending order of popularity) include touch-based devices (45% of requests), external sensors such as force sensors, voice control, and hand gestures, e.g., detected via video processing.

Desire to set and save arrangements for reuse later: Ultimately, the purpose of robotic furniture is to make arrangements that people will use. Many participants expressed the desire to save a particular arrangement and recall it later. P2, for instance, said, "So let us say I want that I arranged my dining room. I want to take a picture feed it to the program, and the program would do exactly the same thing".

Integrated geometric features: When moving multiple chairs, minor offsets often caused collisions; major offsets overwhelmed the user as ChairBots moved in multiple directions. Therefore, we required our improved system to be able to "move in a formation". This involves being able to move relative to the motion of the other ChairBots. Observation of the videos showed that participants found the lack of geometric intuition in the system quite frustrating.

Improved motion control precision: Finally, users expressed frustration that they were not able to move the robots at variable velocities. 75% of the participants reported overshooting via the speak aloud protocol. This issue refers to the precision of the robots' motions especially in terms of truing right and left. For example, P4 said *"The greatest obstacle for the chairs was the rotation.. they turned in different amount each time."*.

4.4 SCREEN-BASED INTERFACE IMPLEMENTATION

The experimental results reported in Section 4.3 formed the basis of user interfaces features that were implemented into the ChairBot platform to improve its usability. This section describes the motivation, and implementation of five technology targets derived from needfinding experiment: **(1) dual interfaces (physical and screen-based), (2) the ability to set and save arrangements, (3) improved positional and velocity precision, (4) the ability to move in formation, (5) the ability to move relative to the geometry of the space**. These are mapped from the discovered features in Table 4.3. The ChairBot platform was extended to fulfill these targets by upgrading the system to enable ChairBots to autonomously move to positions sent from a web-based user interface.

Desired Feature	**Technology Target**	**Technology Description**
Screen-based controller	Web-based UI	A screen-based modality for operating the chairs built with web technologies
Autonomous Motion	Arrangement Template	Commands to save and recall positions enabling furniture arrangements to be reusable
	Moving in Formation	Command to move one robot with low level motion while others maintained a relative shape to that "leader"
	Set Goal	Command to move one robot to a set position and location
Geometric Intelligence	Snap-to-gridlines	Command to set multiple robots to an orientation relative to the room
High Precision	Variable Low-Level Commands	Direct motion commands with multiple speeds capable of angular precision of $\sim 1\,\text{deg}$

Table 4.3: Mapping the implemented technology from desired features discovered in the needfinding experiment.

The implementation of these features required substantial extensions to the baseline system (described in Chapter 3) that advance the ability of robotic furniture arrangement to function as an application:

- A Screen User Interface was implemented on both mobile, and desktop to control ChairBots and trigger autonomous action.
- An overhead camera was added which gives a top-down view of the ChairBots. This streams video over USB to the server where it is both displayed on the website and used to localize the autonomous system.
- Aruco tracking marker fiducials were added to the tops of the ChairBots and, optionally, throughout the scene. This was primarily used to localize the ChairBots and provide overlays to the UI.

- A versatile, greedy path planning script was added to the server which generates ChairBot motion commands based on the sensed world state to enable autonomous features (Algorithm 1).

These additions, illustrated relative to the original system as modules in Figure 4.5, provide the enabling technology to support the inspired features presented in the subsections that follow.

4.4.1 Dual Interface

This subsection describes how the motivation and design of the screen-based user interface, and how its frontend "real-estate" was allocated. The results in the previous section suggested a strong user desire for screen-based inputs in addition to the local physical controls. One participant explained this request via a desire to conduct arrangements from a distance, while others suggested the screen-based user interface include additional features related to memory or precise control. This screen-based user interface replicates the functionality of the physical controller, and also supports the computation features introduced in the rest of the section.

We implemented the screen-based user interface by expanding the original website (shown in Figure 3.4) with a responsive front end that was accessible on a range of screen sizes: including mobile and desktop, as suggested by participants. To make this web-based controller work on a robotic furniture operator's smartphone, it was deployed on a backend server which can serve and communicate with the webpage from any device on its local network.

Four spaces were allocated with different purposes in the interface: selecting active ChairBots, directly controlling motion, enabling autonomous motion (snap-to-grid, formations, and arrangements), and viewing the scene (Fig. 4.6): 1) The space for *controlling multiple ChairBot* consists of a list of checkboxes to enable or disable ChairBot motion. Enables a user to flexibly control multiple ChairBots. 2) The space for *low-level motion control with a virtual joystick* wherein the directions of which correspond to the four possible ChairBot motions: forward, backward, turn left, and turn right. 3) The space for *high-level motion control* includes menus related to the technology target being enabled: arrangements, snap-to-grid, or formations. This space also includes a "big red" stop button at the forefront for quickly neutralizing the ChairBots. 4) *An overhead view* on the scene was enabled by streaming a video feed. Geometrically, the above view allows the user to get a view of the various furniture elements, to aid in arrangement and support safety (e.g., if a collision is anticipated). This view also presented the opportunity to explain autonomous motion by overlaying the current commands and objectives onto the scene.

Compared to the original design, we added a screen-based control option that augments local control, and enables control by a remote operator. More details about the functionalities of each command are included in the following subsections.

4.4.2 Saving and Setting Furniture Arrangements

When users discussed the use cases of robotic furniture, their ability to move themselves was a critical feature. For example, P12 said that saving arrangements is akin to the settings in her car's driver seat which includes location and recline. This subsection describes our implementation of user-in-the-loop system for saving and setting arrangements of ChairBots.

Saving Arrangements: An arrangement is saved by recording a "snapshot" of ChairBots location information from a new overhead camera. The saved location and orientation for all CharBots are recorded to be later recalled as a future **goal**. Saving arrangements is triggered through a button on the main screen of the screen user interface. When pressed, a popup will appear prompting the user to name the arrangement, giving it an identifier that is displayed during **set**. The arrangement, name and coordinates, will then be saved into a JSON file which can be persisted for later use.

Setting Arrangements: Recalling an arrangement similarly involves localization, with the addition of autonomously moving the robot to its desired **goal**.

To trigger this feature, the screen-based user interface contains a button to ”Set Arrangement” which then opens a pop-up containing a list of arrangements previously saved. Once a goal has been defined, a greedy path planning algorithm (Algorithm 1) generates motion commands. This feature can also be used to move between several saved arrangements, e.g., allowing for easy clean up after a space's use, or fluent transitions between multiple segments of an event. We expect this feature will become more useful as users define more arrangements, i.e. its capabilities will increase with use.

Algorithm 1 Greedy Path Planning: This algorithm results in a function representing a movement command.

Require: $goalCoord, goalAngle, botAngle, botCoord, tolerance$
  if $goalCoord$ **then**
    $distance \leftarrow \|botCoord - goalCoord\|_2$
    if $distance > tolerance$ **then**
      return $doNothing()$ {is at goal}
    end if
  end if
  $angle \leftarrow |botAngle - goalAngle|$
  if $angle > tolerance$ **then**
    return $goForward()$ {is facing goal}
  else
    return $turnTowardsGoal()$
  end if

Algorithm 2 Update Goals to Recall an Arrangement: For Chairbot i. $savedBotCoord_i, savedBotAngle_i$ are retrieved from file. The goal coordinates can then be moved to as described in the greedy path planning algorithm.

Require: $savedBotCoord_i, savedBotAngle_i$
  $goalCoord_i \leftarrow savedBotCoord_i$
  $goalAngle_i \leftarrow savedBotAngle_i$
  return $goalCoord_i, goalAngle_i$

4.4.3 Moving ChairBots in Formation

To make it easier for users to move more than one chair at a time, we extended the arrangement feature introduced in the previous subsection to the idea of multiple robots moving together. During the needfinding experiment, users were limited to the number of available hands they had in moving more than one chair at a time. For example, the behavioral analysis of our participant data demonstrated two dominant strategies: **moving in a line** in tight spaces to squeeze through, sometimes angling their bodies to the side to more easily have one chair in front and one behind, or **moving side by side** in which the chairs were to the right and left of the user. Now these formations and more can be set and moved across the space as desired by the user.

The **moving formation** feature was created by expanding upon the ability of user to set and command arrangements 3. We enabled higher-order multi-ChairBot motion using screen user interface (Section 4.4.1) commands and expanding the autonomous arrangement system (Section 4.4.2). However, instead of setting goals based on the absolute position in a room, in a formation ChairBot goals are set relative to a single primary ChairBot. This primary ChairBot can be moved around the scene and all of the secondary ChairBots will maintain that formation for as long as it is active by updating their goals in real time. Formation goal updates only apply to translations, as attempting to preserve the formation over rotations causes goals to quickly "jump" long distances. This results in long delays (¿1sec) in the time for the ChairBots to move to their goal and reset the formation. Minimizing the delay of resetting the formation results in smoother operation and a better user experience.

This feature allows for a single user to move several ChairBots.

4.4.4 Integrating Geometric Knowledge of Space

During the needfinding experiment, users expressed an expectation that the chairs to have geometric knowledge of their surroundings. For example, it is common for

Algorithm 3 Algorithm to Update Goals to Move in Formation: For Chairbot Id i which is following a primary ChairBot. $primaryCoord$, $primaryAngle$, are retrieved live from the localization system. $savedBotCoord_i$, $savedPrimaryCoord$, $savedPrimaryAngle$ are retrieved from file. The goal coordinates can then be moved to as described in the greedy path planning algorithm.

Require: $primaryCoord, primaryAngle$
Require: $savedBotCoord_i$
Require: $savedBotCoord_p, savedAngle$
  $offset \leftarrow primaryBotCoord - savedPrimaryCoord$
  $goalCoord_i \leftarrow offset + savedBotCoord_i$
  $goalAngle_i \leftarrow primaryBotAngle$
  return $goalAngle_i, goalCoord_i$

people to arrange furniture relative to the walls of the space or existing furniture. Therefore, the next features we developed allow for chairs to move relative to existing features.

Snap-to-geometry is a feature that allows the user to command the chairs relative to the geometry of the room or its objects (e.g., parallel to a table). Snap-to-geometry can be defined for room-centric geometries relative to the walls of the room, or furniture-centric geometries relative to an object in the scene. For the purpose of this implementation, we propose a simplified case only for orientation. To "snap" the ChairBots into position, the user selects from a list of room-centric and table-centric gridlines in the screen-based UI. This enforces the robot to face towards a direction by setting a goal angle relative to the camera (room-centric), or a fiducial placed on an landmark in the scene such as a table or another ChairBot (furniture-centric). This is formalized in Algorithm 4. This allows the Chairbots to move around the space while "snapping-to" an orientation.

Algorithm 5

Require: $objectAngle$
  $goalCoord_i \leftarrow$ **false**
  $goalAngle_i \leftarrow objectAngle$
  return $goalAngle_i, goalCoord_i$

These new geometry-based movement capabilities reflected the ways in which users presumed the robot would have knowledge of its application, i.e., that robotic chairs understand the geometry of the room and that furniture arrangement is often organized relative to both the room and each other.

4.4.5 Meeting User Expectations of Precision

A second result from the experiment was that 92% of participants (11/12) expected the robotic chairs to move with higher precision. Similarly, while the original system moved at a fixed velocity (330 mm/sec), users wanted the motion to be proportional to the force they exerted on the sensors (i.e., "easing up" on the button to slow down the ChairBot).

Improving the Motion Precision: While the original software implementation was calibrated to rotate the chair at five degree increments, participants perceived the difference between 45 degrees and 50. We updated the unit of motion to one degree to account for this. This underscores the attention to geometry that users may have when moving future robotic furniture systems into their final positions.

Proportional Velocity Control: Because of the dual user interface, our improved precision involved separate solutions in the physical and screen-based interfaces. We replaced the capacitive contact sensors on the physical interface with **force-sensitive resistors** (FSRs), which output varying voltages depending on how hard the user pushes on them. We use the FSRs to trigger the robots to move in incremental steps at three levels of relative velocity (110, 220, and 330 mm/ sec) to enable variable speeds. For proportional control on the screen-based interface, we instead implement a **virtual joystick controller**, involving a "draggable" circle that is centered in a larger circle. The inner circle can be dragged to the edge of the larger circle to indicate a proportional motion command.

4.5 DISCUSSION

Desirable features for a multi-robot furniture system were found via a needfinding experiment and concretely defined by integrating them on the ChairBot platform. These features show how participants focused on a desire to more effectively operate the system using **intelligent autonomy** controlled at a **diverse levels of abstraction** using a **screen-based modality**.

Our empirical experiment helped surface user expectations of how robotic furniture will behave, augment user control with intelligent autonomy features, and invent task-specific commands. Learning about participant expectations of robotic furniture revealed flexible user perspectives about when robotic furniture systems may be used: like moving out of the way so one can more easily clean their dining room, or forming the same arrangement on when moving from one house to another. Participant comparisons of using the robotic chairs to make arrangements versus using non-robotic chairs helped inform the design of various novel features for our the robotic furniture system.

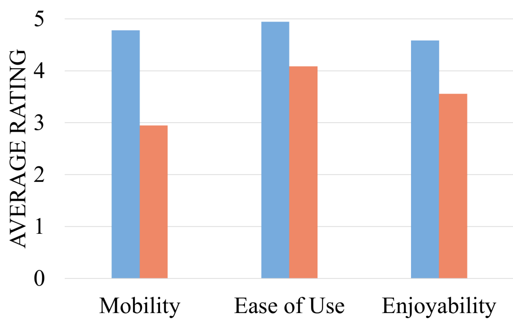
Expanding upon the baseline physical robot system and touch-based on-robot control interface, we integrate participant suggestions about desired features into our redesign and extensions of the robotic system. For example, we improve the hardware precision by adding force-sensitive resistors and creating a screen-based interface to offer abstract controls at a distance. This screen-based interface is further utilized to act as a front-end controller of our novel saving and setting arrangement features, as well as our formation-based and automated snap-to-geometry motion features, intended to increase the efficiency and usability of moving several or many ChairBots at a time.

The fact that many of these user-centric features exist at a higher level of abstraction is novel. Previous research with the ChairBots, and furniture-based WoZ platforms, exclusively leveraged low-level motion commands. The needfinding experimental results suggest that people want and expect robot chairs to have high levels of autonomy which leads to the abstract affordances discussed in Section 4.4: arrangement templates, moving in formations, and snapping to grid. However, the final feature, low-level motion, shows how this expectation for high levels of abstraction is nuanced. The diverse range of arrangement behaviors and the dissatisfaction with the imprecise level of control given by the prototype interface illustrates how fickle users are when it comes to arranging furniture suggesting that precise low-level control may be necessary even for sophisticated robotic furniture capable of high levels of autonomy.

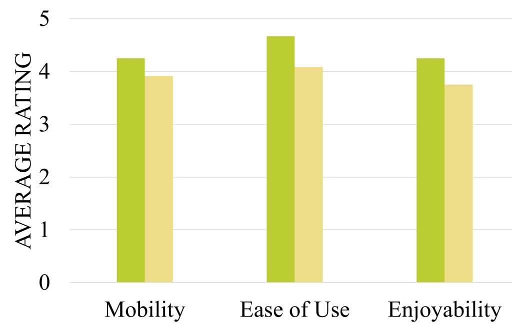
The addition of a screen-based interface enables these higher levels of control. Robot furniture benefits from the inclusion of a screen-based digital interface in addition to the physical local control tested in this experiment.Dual interfaces are useful because multi-robot furniture, as an application, must be usable by users in proximity (sitters) and those rearranging them from afar (wranglers). At the start of this experiment, we realized that sitters wishing to move ChairBots may resort to legacy affordances (e.g., pickup and move) rather than set up a digital interface (e.g., download an app). However, we found the digital interface better suited for highly abstract command affordances involving multiple robots as physical interfaces are constrained by the cost, and time required to augment the hardware for each robot in a fleet.

Advancing a low-cost research platform enables future research. Furthering the technical reliability of the ChairBot system also creates opportunities for future research, and we have published the software for our multi-ChairBot furniture arrangement on an open-source GitHub repository where it will be improved over time. The ability to more effectively operate furniture robots is a requirement for the successful adoption of robotic furniture as a labor-saving application and the use of these robots in social multi-robot HRI experiments.

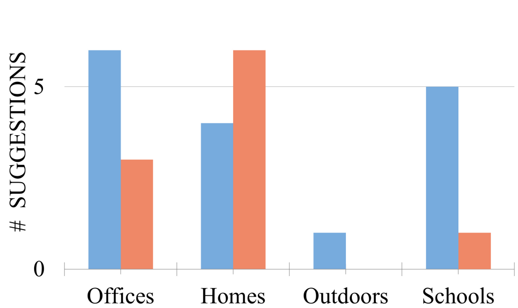
The next chapter discusses how we extended this platform to evaluate how the features for multi-robot furniture identified in this chapter suited remote teleoperators arranging multi-robot furniture to suit human requirements during a multi-phase event.



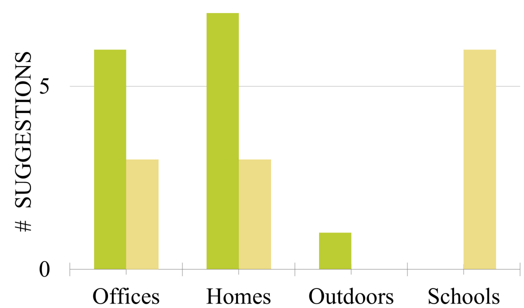
(a) Ratings for Chair Types



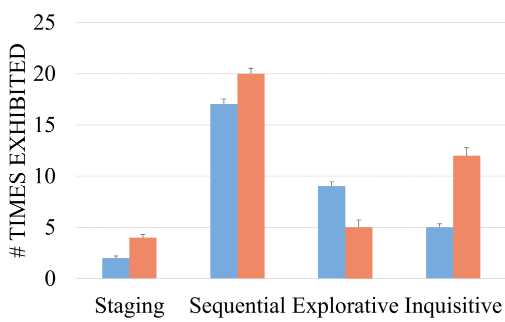
(b) Ratings for Space Types



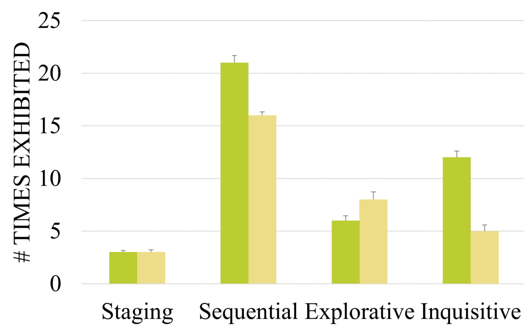
(c) Suggestions for Chair Types



(d) Suggestions for Space Types



(e) Behaviors for Chair Types



(f) Behaviors for Space Types

Figure 4.4: Results from the empirical experiment. Bars are color-coded to represent chair types (Non-Robotic vs. Robotic)as well as space types (Around Table vs. Empty) The ratings correspond to a 5-point Likert Scale averaged (mean) answers from all participants. Survey responses show the impact of our main manipulations: (a) robotic vs. non-robotic chairs, (b) open versus preset spaces. types on user's questionnaire results. We also (c) count the uses-cases that participants mentioned, (d) and suggestions of types of spaces in which chairs can be used. Finally, we consider (e) how chair type influenced the number of times users exhibited specific rearrangement behavior, and (f) what behaviors were used in what space types.

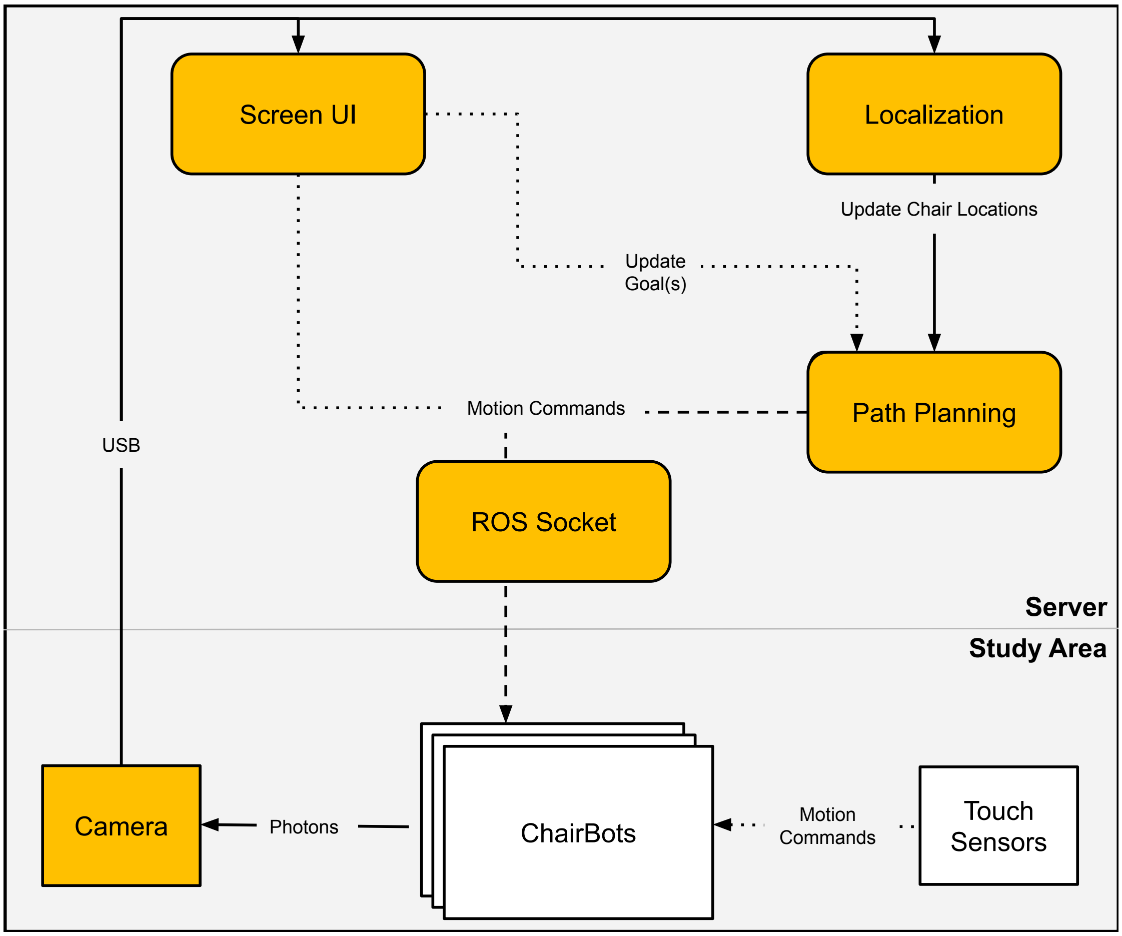


Figure 4.5: Diagram showing key modules of the system with changes highlighted. This final architecture enables features identified during the needfinding experiment. The new modules were added to enable features discovered during testing and survey. Original modules include modules used during the experiment. Modules with rounded corners represent modules that exist primarily as software, whereas abrupt corners represent modules with a physical presence in the experiment area or scene. The arrows represent Autonomous ——— , Semi-Auto - - - - , and User Driven ………… .

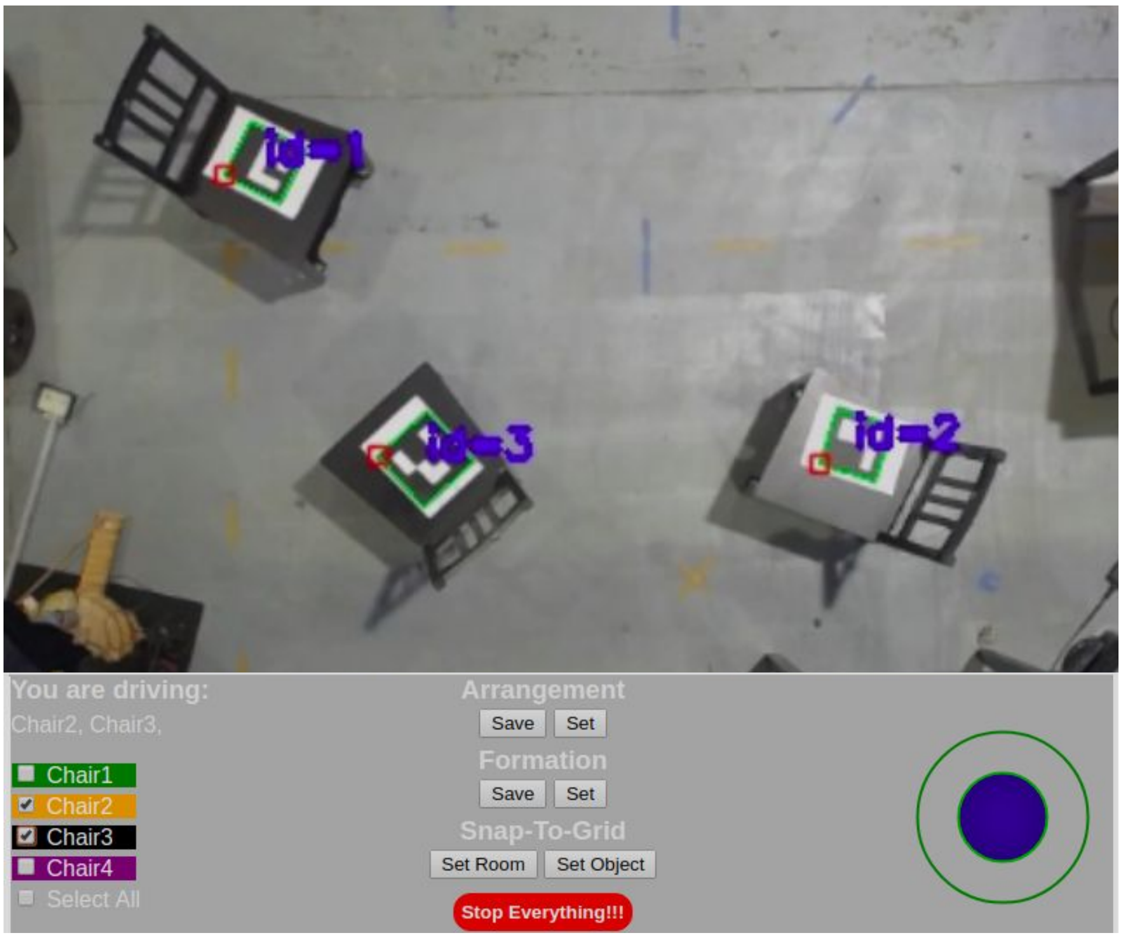


Figure 4.6: Screenshot of the ultimate screen-based user interface. It consists of a live video stream of the room, and affordances for controlling the ChairBots. Affordances include a ChairBot selector, autonomous capabilities to set and save both arrangements and formations, and an option to snap to an orientation as well as low-level motion (with the joystick) and emergency stop controls. A demo video is available at [65].

Chapter 5: Application-Centric Evaluation of Remote Furniture Arrangement

This chapter presents an application-specific evaluation of the screen-based user interface by 1) extending the screen-based user interface presented in Chapter 4 to enable remote teleoperation, and 2) an exploration of the utility of commands at varying levels of abstraction for a creative and realistic furniture rearrangement task with remote participants. [1] A unique part of this experiment was the method of having remote participants control real robots from the safety of their own homes, as required and inspired by the COVID-19 Pandemic. The results of this experiment proved the feasibility of remote furniture arrangement with affordances at a diverse range of abstractions.

5.1 INTRODUCTION

The screen-based user interface was extended to enable fully remote tele-operation over the web and refined to include three easy-to-learn command affordances at different levels of abstraction: set preset arrangement templates, set positional goal, and low-level direct commands. To test the difference between the affordances with higher levels of abstraction, three versions of this interface were created which either excluded arrangement templates, excluded goal setting, included all three affordances. Participants (N=12) were asked to use the user interface versions to rearrange ChairBots based on three arrangement prompts for phases of a birthday party: eating cake, a magician performance, and dancing. Manipulations were balanced within-subjects. We considered this realistic scenario to be a creative task because participants were only told how the space was going to be used, and

[1] This work was published in [66] and presented at the International Conference of Social Robotics (ICSR) by myself, Mark-Robin Giolando, and Heather Knight.

not where to move the robots (as was done in Chapter 4 and most other evaluations of multi-robot user interfaces).

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 based on their interpretation of an open-ended 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 command abstraction is best suited for the task of arranging robotic 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 for each prompt, found no differences between tested UI Types, and found our novel web-based interface easy to use which supports the viability of remote robotic furniture arrangement as an application.

5.2 EVALUATION EXPERIMENT METHODS

This section describes our experimental manipulations, metrics, and procedure. A multi-robot system consisting of these ChairBots was chosen due to the implication that robotized furniture is a multi-robot system and the fact that ChairBots have been previously studied in past HRI research[3, 17, 19, 39]. 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[4].

5.2.1 Technology

Our implementation of **multi-robot furniture** involves three robotic chairs remotely tele-operable from a website. The ChairBot, originally designed by [39], 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 user interface make up our multi-robot furniture system[2]. 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 user interface are shown in Figures 5.3, and 5.1 respectively.

Prior research on our ChairBots user interface established the desire for a screen-based controller, and some of its primary features for control[19]. 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 to enable it to run over the internet [65] and simplified the web layout, extending image overlays, and adding a method to set individual ChairBot locations and orientations ("set goal")[68].

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

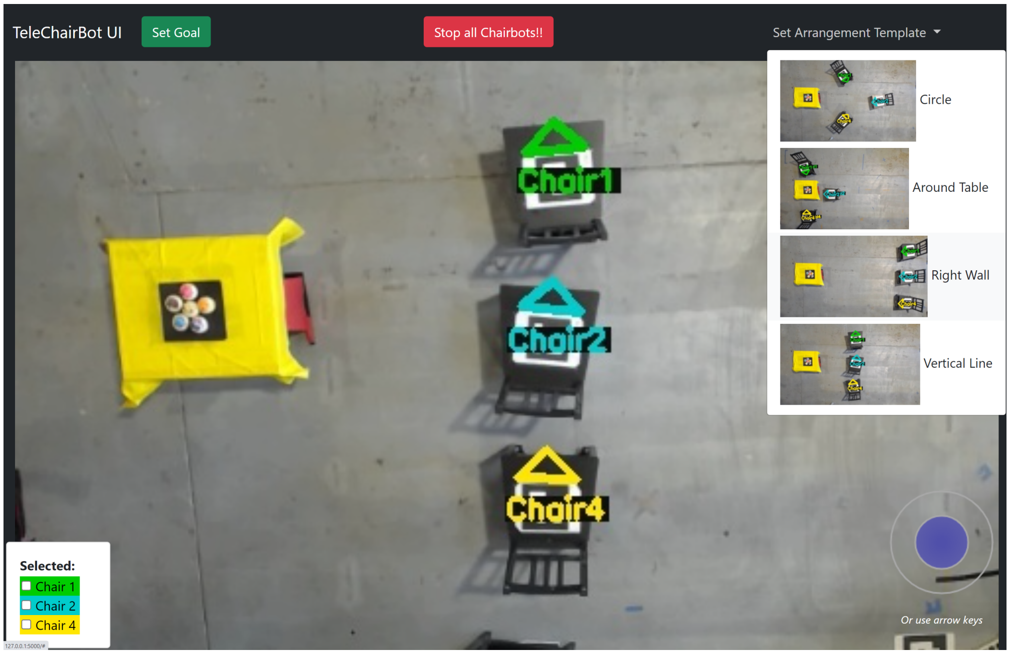


Figure 5.1: The Tele-Chairbot UI with ChairBots in their starting positions. A live overhead video feed shows the room which includes the ChairBots and a non-robotic table with cupcakes. A joystick on the bottom-right can be used to send low-level motion commands. The top bar has the higher-level commands: set goal, and set arrangement template.

5.2.2 Manipulations

During this experiment, two manipulations were introduced for each trial with three states each: party phase, and UI Type. These were evenly distributed such that every participant saw all three states over three trials. Order and combinations were balanced between participants for both manipulations (with the exception of the "Both" UI Type due to how participants were trained).

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

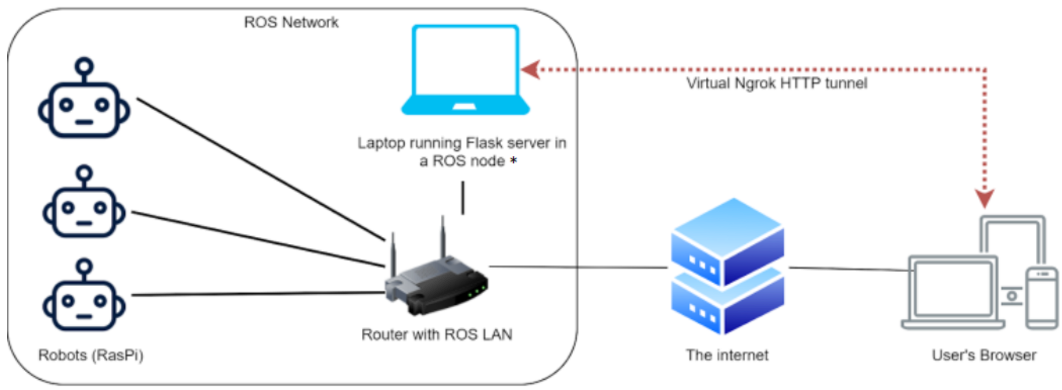


Figure 5.2: Networking diagram of the ChairBot web backend that enables a remote participant to operate a remote robot from a website over the internet. *Demo code for this server available at https://github.com/stoddabr/ros_flask

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 command abstractions: (1) **goal-based commands** in which users can move one chair at time with by clicking to set a final waypoint location and orientation, and (2) **arrangement template**, in which a drop down menu of present arrangement graphics can be selected from. We also provided a screen-based joystick for general fine-tuning for all modes. 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 command abstractions.

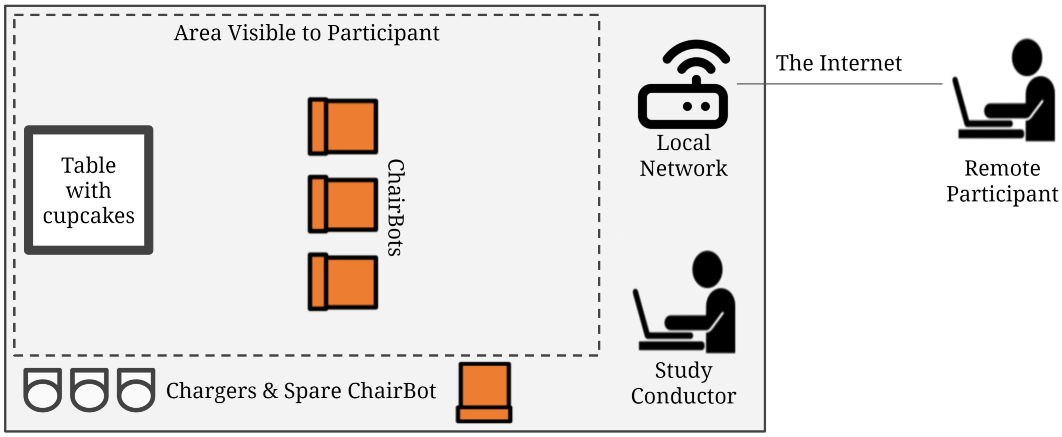


Figure 5.3: A remote participant interfaces with the system using the web-based user interface by watching a camera feed with an overhead view of the research area. A researcher locally monitors the ChairBots and facilitates the experiment.

5.2.3 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[8]. The post-trial survey included 7-point Likert scales from the NASA-TLX survey[28] 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[3].

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

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

of participant 3's video[4].

5.3 EVALUATION EXPERIMENT RESULTS

This section presents the results of these experiments: (1) participant party phase prompts resulted in very similar arrangements for two of the three phases, (2) both user interface command abstractions were rated highly by participants, and (3) participants reacted positively to the user interface.

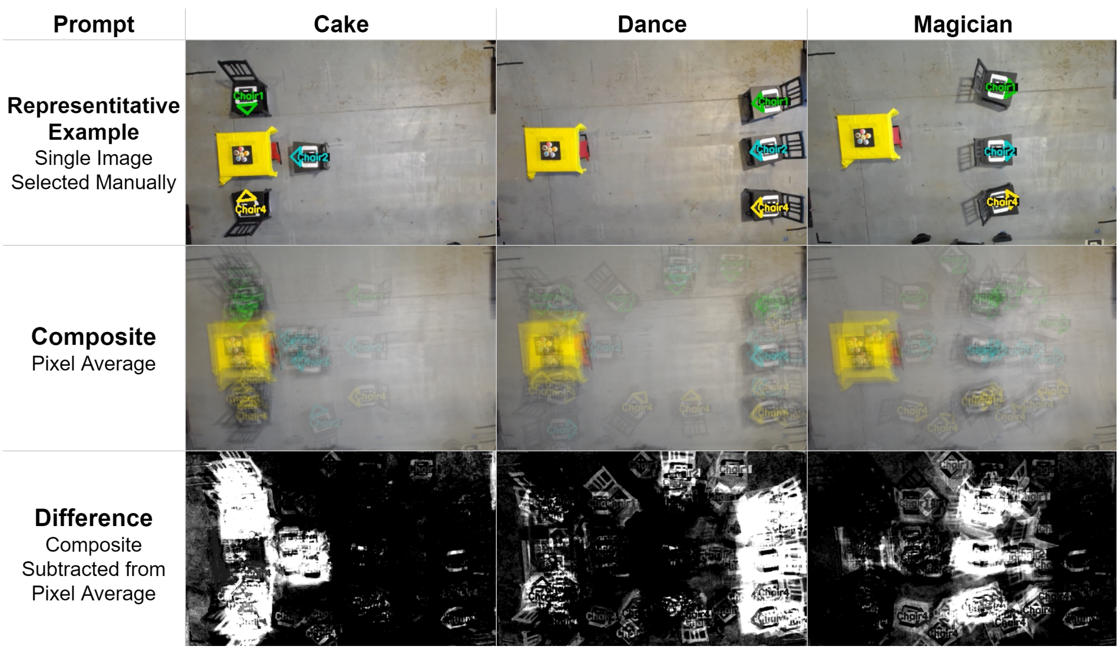


Figure 5.4: Images in a table showing final arrangement information. The Representative Example was manually chosen to to show a typical/median arrangement. The Composite image was created from the mean of all arrangement images for that prompt. The Difference image shows the difference between the composite 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

[4]Available at https://www.youtube.com/watch?v=8I1Hz5R4jxk

arrangements for trials shown in Figure 5.4. 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 will 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 exhibiting 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.

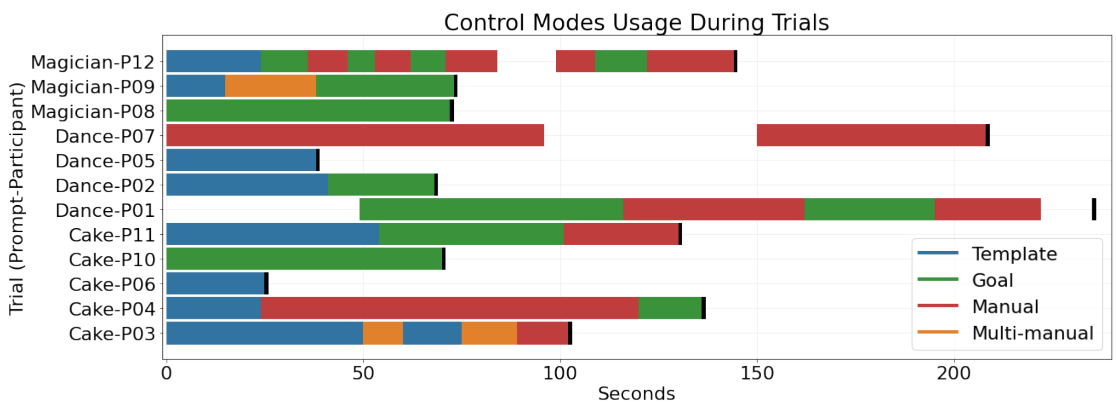


Figure 5.5: Different commands used over time for trials in which all controls were enabled (i.e., trials where UI Type was *Both*). Empty areas represent times when ChairBots were not moving, and the participant was not interacting with the user interface (anecdotally, they were thinking or planning their next command during this time). 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 required for trials.

No Command Abstractions Were Favored. Participants were exposed to two command abstractions (goal-based commands and arrangement template), however, neither UI Type 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 command was used and for how long was collected, as shown in

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

Figure 5.5, as was the final command abstraction used to position the chairs. 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 commands were triggered 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 5.4) suggests that participants found differing utility for each command abstraction.

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 [8], 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 5.1. 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 5.1, nor between exit survey responses. This fails to support H4 as participants did not prefer using higher-abstraction commands.

5.4 DISCUSSION

Three major findings emerged from the results analysis of the results generated from this experiment applicable to both the field in general, as well as future iterations of multi-robot furniture. First, the high usability and application use ratings overall indicate the **viability of tele-operating** multi-robot furniture, as operators enjoy using the system and find the final arrangements it enables to be effective. Second, though some UI Types were more popular than others (e.g., goal based commands was more popular than arrangement template), participants maintained a preference for any interface with **diverse command abstractions**. Third, the strong mapping between final arrangements and Party Phase between the various participants indicates the **repeatability of furniture arrangements**, and suggests the integration of such patterns into user commands is useful.

Participants were able to create satisfying furniture arrangements, supporting H1. Additionally, all participants rated the system better than moderately usable. The resulting average SUS rating of 75 ($\sigma = 10$, "Good" as per [8]), and positively skewed survey scores support H3. However, the low number and higher-than-average technical competency of recruited participants may have confounded this result.

Users found all UI Types to be similarly useful as the exclusion of the goal and arrangement template higher-level affordances did not have an effect suggesting they are redundant. Excluding the low-level motion commands, as tested in pilots, appeared to render the system inflexible to the point of being unusable so that condition was not tested during the main experiment where time was limited. This can be explained through two different lenses: through the task of furniture arrangement, and the application of HRI-based levels of abstraction frameworks.

The task of arranging furniture can be broken into two steps: moving furniture to roughly the desired position, and fine-grained adjustments. The former step is where the higher-level abstractions are useful, whereas fine-tuning is only possible with low-level motion commands. Therefore, the goal and arrangement template affordances can be considered redundant as they are useful for the purpose.

The goal and arrangement template affordances can also be shown redundant by applying the HRI-based Level of Human Control Abstraction (LHCA) framework. According to the LHCA framework, both goal and template affordances are classified as *parametric* abstractions so this theory predicts they are redundant [33]. This supports the application of level of abstraction frameworks, LHCA or otherwise, to identify such redundancies early on in the design process.

However, measurable effects may also being to appear as the number of robots increases. The user interface was only tested in this experiment with three ChairBots. Applying the theory of *fan-out*, the workload for using the "set goal" affordance is expected to increase, whereas it is expected to stay roughly the same when using "arrangement template" affordances. Therefore, increasing the number of robots may cause differences between the UI Types to become measurable. Future work on multi-robot systems can both heed and address this discrepancy.

Party phase corresponded to furniture arrangement pattern, as illustrated in Figure 5.4 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 suggests arrangement towards an object or place whereas the latter suggests 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.

Variations from these patterns were found to be caused by contextual assumptions on how the space was going to be used. 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 designing robotic furniture systems for different social or regional application domains.

Chapter 6: Discussion

The results from our needfinding (Chapter 4) and application-specific evaluation (Chapter 5) contribute:

1. Detailed **technology** requirements for effectively tele-operating a multi-robot furniture system include a screen-based modality, appropriate autonomy, and embedding geometric intelligence. These originated in prior furniture-based HRI WoZ experiments (Chapter 3), was rebuilt and extended based on participants' expectations in a needfinding experiment (Chapter 4), and proved to be useful in a realistic evaluation experiment (Chapter 5).

2. A deeper understanding of desired human interactions with robotic furniture **applications** during a multi-phase events, from local user control as conducted in Chapter 4 to remote rearrangement in Chapter 5.

3. The development of task-specific **command abstractions** through a UCD-based needfinding experiment, as presented in Chapter 4, was shown to lead to useful affordances for multi-robot furniture which may be extended to other domains.

4. The novel **remote experiment** method of having a participant remotely tele-operate real robots over the internet, as conducted in Chapter 5, overcomes some common obstacles encountered when recruiting participants.

The rest of this chapter will discuss these topics relative to prior and future work.

First, the **technology** in robotic furniture was expanded through the development of a user-centric screen-based interface, initially for general multi-robot furniture movement (Chapter 4), and then for enabling a multi-phase event (Chapter 5). Additionally, we established two broadly reusable concepts for multi-robot arrangement: geometric-based intelligence (e.g., moving relative to the wall of a room or another piece of furniture), and variable autonomy (i.e., appropriately automating actions based on user requirements). These improvements extended prior robotic furniture used in HRI experiments (Chapter 3). The implementations of screen-based user interfaces with both autonomy and geometric intelligence presented in Chapters 4 and 5 scaffolds the efficient yet flexible command abstractions needed to improve operator efficiency relative to the original interfaces, described in Chapter 3, which only contained low-level commands.

Effectively operating multi-robot furniture requires a *screen-based* interface as demonstrated in the interface and experimental results presented in Chapters 4 and 5. As mentioned in Section 3.1, a physical interface flexible enough to enable complicated commands will either be too expensive (e.g., a touchscreen on every ChairBot), or too complex (e.g., many dedicated buttons for each command). That flexibility is necessary to implement the abstract commands discovered in the Chapter 4 needfinding experiment. Parallel to this technical requirement, participants in the needfinding experiment not only suggested but *expected* the ChairBots to be controllable using a screen-based user interface. The remote participatory experiment in Chapter 4 was only made possible by a screen-based interface working over the internet due to, but also inspired by, social distancing requirements during the COVID-19 pandemic. These technical requirements, based on user expectations, and enabled use-cases support the use of a screen-based modality for operating multi-robot furniture.

The traits desired by participants in our Chapter 4 needfinding experiment established the importance of appropriate *autonomy*, and *geometric intelligence* to be embedded into robotic furniture. For example, relatively unsophisticated autonomy consisting of a “greedy, blind, and naive path planner” described in Section 4.4 was enough to enable participants to successfully create realistic multi-robot furniture arrangements in Chapter 5. A system with more robots or a more chaotic environment (i.e., any real-world application) may require more robust algorithms as issues, like collisions, will become more prevalent. Similarly, the implementations of geometric intelligence were limited: Chapter 4 proposed a command abstraction wherein ChairBots "snap" to an orientation relative to the walls of the room, and Chapter 5 included preset arrangements templates based on the room (e.g., the "Around Table" arrangement template in area 1b of Figure 6.1). As with autonomy, the limited use of geometric intelligence here is based on the relative simplicity of the implementations done in this thesis. Incorporating existing furniture knowledge to improve geometric intelligence (e.g., relative to other furniture or lighting based on rules from feng-shui), and more sophisticated autonomy (e.g., better path planners [42] or collision avoidance sensors [26]) may be required for complex real-world applications. However, as shown through the success in Chapter 5, neither perfect autonomy nor highly sophisticated geometric intelligence is necessary for successful tele-operation.

Second, this work has expanded knowledge about human expectations of robotic furniture as an **application**. We found that people naturally use abstractions to discuss what they want robots to do and have demonstrated that rearrangement is viable for human-in-the-loop control in the needfinding experiment of Chapter 4 and the remote-teleoperation evaluation of Chapter 5. Robotic furniture as an application opens new possibilities by reducing the labor required to arrange furniture for multi-phase events where it can be used in-person and operated remotely, and these demonstrations have moved the world one step closer to this reality.

Human expectations for where and how robotic furniture may be used highly correlate to where furniture is found today. The range of applications for multi-robot furniture as suggested by participants in Chapter 4 was focused around familiar, indoor spaces such as schools, businesses, and homes with one account suggesting robotic furniture may be used outdoors. The ability to enable a multi-phase event in the same space was proven through the successful furniture arrangements created by remote tele-operators for a multi-phase birthday party in Chapter 5. This is in contrast to other work deploying robotic furniture in social HRI settings where getting participants to interact naturally with robotic furniture requires careful design and prototyping [63]. Humans naturally assume robotic fur-

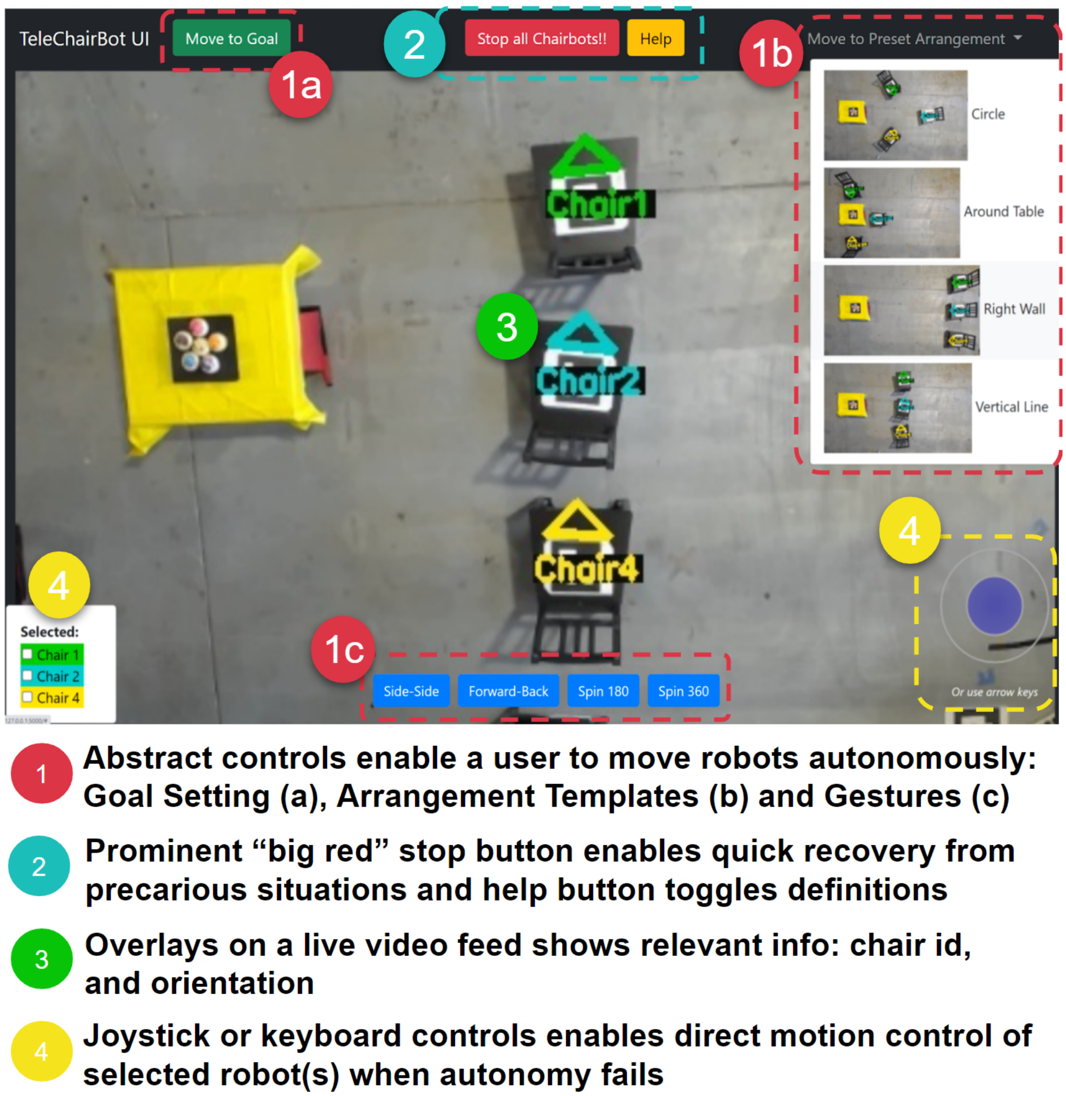


Figure 6.1: Final user interface with key affordances and features explained.

niture is to be used as furniture compared to apparently novel roles such as social actors.

Most realistic scenarios involve humans interacting physically with robotic furniture, unlike the remote tele-operators in Chapter 5, which has two design implications. First, legacy affordances must be preserved in robotic furniture; our ChairBot has springs to make it safe to sit on. Second, enabling co-located interactions is important; a user must not be required to open the screen-based interface to accomplish simple tasks like moving a ChairBot out of a busy walkway. The best way to enable co-located control may be enabled by implementing a physical interface, such as the one used in the needfinding experiment, in parallel to the screen-based interface as they both serve different user roles. This dual interface was suggested by participants during the needfinding experiment in Chapter 4. The physical interface is useful to anyone wishing to have a seat, with the screen-based interface is useful to anyone wishing to wrangle multiple robots at once.

Third, our investigations uncovered reusable, task-specific **command abstractions** that enable efficient multi-robot wrangling for furniture applications with methods being applicable to other multi-robot domains. Although prior research has identified command abstractions useful for general multi-robot motion, such as moving through waypoints or to a goal, this thesis proposes four multi-robot commands specific to robotic furniture: autonomously moving multiple ChairBots to a preset *arrangement template*, moving multiple ChairBots while maintaining a *formation*, *snapping* ChairBot orientations along gridlines. All of these enable a single human to effectively operate multiple furniture robots at once, effectively breaking past the limit predicted by fan-out theory. The trade-off for this efficiency is the loss of fine-grained control which is required for tuning and experimenting with furniture arrangements. The evaluation experiment in Chapter 5 found the user interface useful for furniture arrangement when it contained diverse command abstractions to enable both creative and efficient control. The system was robustly performative across all tested UI Type manipulations – a desirable trait as the utility of these command abstractions is stable to variations in affordance implementations. Other multi-robot domains can apply similar UCD methods to derive task-specific command abstractions.

However, the number of robots used was low relative to other multi-robot systems, which impacted the effect of using various affordances. Increasing the number of robots in a system increases operator workload [13, 40, 52], so rerunning experiments with multi-robot furniture with more robots, either real or simulated, might yield different results, especially, since furniture arrangement requires some creativity and most current evaluations of multi-robot systems utilize tasks with well-defined objective goals like search-and-rescue.

Our method of applying UCD methods to first understand human expectations and desires before designing an interface enabled us to base our system around effective command abstractions. How and when UCD methods, which were originally developed in the HCI domain, carry over to HRI is still an open area of research. Qualitative data from our UCD-inspired needfinding experiment directly mapped to the command abstractions shown to enable participants to rearrange furniture in an application. The finding that participants were able to arrange furniture successfully using all versions of the user interface in Chapter 5 further supports this. This success supports the practice of leveraging UCD methods to develop command abstractions for complex robot systems. Future work may consider applying similar UCD experiments with prototypes early in the development of complex robot systems to discover valuable insights, such as appropriate command affordances and human expectations of autonomy.

Fourth and finally, our novel **remote experiment method**, wherein participants remotely tele-operated real robots from a website, was a unique contribution of this work employed to overcome obstacles in recruiting participants for the evaluation experiment in Chapter 5. This setup is illustrated in Figure 5.3. Developing this method was necessary to run our evaluation experiment due to social distancing laws enforced during a deadly pandemic, and can be used to recruit participants from anywhere on Earth with an internet connection. For example, to recruit participants from a more diverse pool than is conveniently available on College campuses, domain experts, or a targeted user group (such as the elderly or disabled). This combines the benefits seen with methods involving simulated robots, or pre-recorded videos with the desirable characteristics that come with running a real-robot experiment in real-time. Moreover, this HRI experiment style is ecologically valid, in that remote human-in-the-loop operation is a paradigm with many novel control algorithms and applications being proposed over recent years [35, 60, 48].

Building the interface on a website also offers a rich suite of easy-to-integrate tools pioneered by the HCI community and funded primarily by the advertisement industry for tracking clicks, mouse motion, and even eye motions. Such tools were used in Chapter 5 to collect images of the final ChairBot arrangements as shown in Figure 5.4. This novel methodology shows how future researchers can overcome recruiting challenges by leveraging a remote interface.

Many opportunities for future expansion exist based on our contributions to improve user interfaces for multi-robot furniture.

Figure 6.2: Annotated portfolio of the final ChairBot system. The collage exhibits the ChairBot system during studies (left & top right), testing (center-left), performances (center-right), and other deployments including one done during Halloween (right).

Chapter 7: Conclusion

This thesis explored effective user interfaces for rearranging multi-robot furniture. First, results from a human needfinding experiment inspired features for a screen-based interface with affordances specific to robotic furniture arrangement. (Chapter 4). Next, this screen-based interface was extended to enable fully remote teleoperation over the web and evaluated with participants acting as remote operators. The participants in the latter experiment reported the system to be usable when diverse command abstractions were available, supporting the feasibility of remote multi-robot furniture arrangement (Chapter 5).

This research contributes to a deeper understanding of technology, applications, command abstractions, and evaluation methodology for multi-robot furniture. Technology was presented through the implementations of screen-based user interfaces (Figures 4.6, 5.1, and 6.1) with affordances for user-centered command abstractions, appropriate autonomy, and embedded furniture-specific geometric intelligence. Two applications of multi-robot furniture (general motion in Chapter 4 and a multi-phase event in Chapter 5) were successfully demonstrated using a system consisting of three ChairBots supporting the feasibility of and contributing practical knowledge for real-world deployments.

These explorations of the robot furniture application resulted in developed command abstractions and affordances (as detailed in Figure 4.6) that contribute effective methods for commanding a multi-robot system for the creative task of furniture arrangement: arrangement templates, moving in a formation, snapping to an orientation, navigate to a goal, and moving with variable speeds. During the evaluation experiment and pilot in Chapter 5, these commands were found to work best when multiple affordances from diverse levels of abstractions were included on the interface supporting the use of similar abstraction diversity on interfaces for creative tasks. The UCD-based method used to derive such task-specific abstractions (Chapter 4) and novel method to evaluate them remotely over the internet (Chapter 5) can be used by future work on designing user interfaces for complex robot systems.

The current robot system and evaluations also leave many opportunities open for future work as discussed in Chapter 6. Relative to other multi-robot systems, the three ChairBots used in both experiments leave a gap in the multi-robot space for work on systems with many more robots to emulate realistic applications such as a conference (as many conferences have to seat hundreds of attendees). Such higher-order multi-robot systems may invoke different results when comparing command abstractions which the evaluation experiment in Chapter 5 failed to find a statistically significant difference. More realistic complex environments or robot systems may require more robust autonomy (e.g., better path planners [42] or collision avoidance sensors [26])), sophisticated geometric intelligence (e.g., relative to other furniture or lighting based on rules from feng-shui), socially inspired motion (e.g., via the gesture command abstraction proposed in [67]), and even higher command abstractions (e.g., inspired by swarm robots [40]). Future work can consider applying the methods used in this work, UCD-based experimental needfinding and a remote evaluation experiment, to these extensions as well as other robotic domains which desire to improve their user interfaces.

Furniture is intrinsically tied to spaces that humanity inhabits; therefore, the use of robotic furniture will always have humans in the loop. Whether a person is giving the system higher level directives, fine-tuning an arrangement, or using formations to move multiple robots efficiently, robotic furniture supports the desires of the people who intend to sit on them.

APPENDICES

Appendix A: Needfinding Experiment Questions

A.1 NEEDFINDING SEMI-STRUCTURED INTERVIEW

These scripted questions were generally followed for all participants with impromptu follow-up questions being asked for clarification or to follow an interesting thread of conversation as needed.

After every trial the following questions were potentially asked verbally by the Study Conductor:

- What did you do?
- Where do you see this setup used?
- What were you thinking?
- Do you want to try another setup?

After all trials, during the final interview the following questions were asked verbally by Study Conductor:

- Giving your experience with the ChairBots, what would you desire to see? Do you want to act them out?
- What would you like to try next?
- What tasks did the chairs seemed best suited for?
- Did you find the way the chairs traveling together to be effective? What uses could you imagine for robot chairs?
- Do you have any additional comment or feedback for us to help improve the robots?

- How and where would you see the ChairBots suitable?
- How have your expectations of robots and their benefits changed over the course of the experiment, if at all?
- What advice would you give to other people controlling the chairs?
- What insights do you have for future robot designers?
- Do you think this kind of robot could be useful? Why and for what?
- What would you like to see autonomous robots do in a similar situation?

A.2 NEEDFINDING SURVEY QUESTIONS

The following two pages were given to the participant after each trial to write responses to.

Participant # ____________
Date ____________
Chairs Type ____________

Section 1: Mobility	
Rate the chairs by circling the best descriptors for each of the following: 1: The chairs motions were expected *Disagree 1 2 3 4 5 Agree* 2: The chairs motions were appropriate *Disagree 1 2 3 4 5 Agree* 3: The chairs motions were natural Disagree 1 2 3 4 5 Agree	Do you think the chairs were successful in accomplishing the intended tasks? If so, how? ______________________________ ______________________________ ______________________________ ______________________________
Section 2: Ease of use	
Rate the chairs by circling the best descriptors for each of the following: 4:I found the chairs complex to use *Disagree 1 2 3 4 5 Agree* 5: I thought the chairs were easy to use *Disagree 1 2 3 4 5 Agree* 6: I found the chairs very cumbersome to use *Disagree 1 2 3 4 5 Agree*	Did you encounter any obstacles? If so, what obstacles did you encounter? Did it influence the way your drive the chairs? ______________________________ ______________________________ ______________________________ ______________________________
Section 3: Enjoyability	
Rate the chairs by circling the best descriptors for each of the following: I liked interacting with the chairs *Disagree 1 2 3 4 5 Agree* My interaction with the chairs was pleasant *Disagree 1 2 3 4 5 Agree* My interaction with the chairs was **complicated** *Disagree 1 2 3 4 5 Agree*	Was there anything positive or negative that happened? Please describe it. Did it influence the way you controlled the chairs? If so, how? ______________________________ ______________________________ ______________________________ ______________________________

Participant # ____________
Date ____________
Chairs Type ____________

Section 1: Mobility	
Rate the chairs by circling the best descriptors for each of the following: 1: The chairs motions were expected *Disagree 1 2 3 4 5 Agree* 2: The chairs motions were appropriate *Disagree 1 2 3 4 5 Agree* 3: The chairs motions were natural Disagree 1 2 3 4 5 Agree	Do you think the chairs were successful in accomplishing the intended tasks? If so, how? ____________ ____________ ____________ ____________
Section 2: Ease of use	
Rate the chairs by circling the best descriptors for each of the following: 4:I found the chairs unnecessarily complex *Disagree 1 2 3 4 5 Agree* 5: I thought the chairs were easy to use *Disagree 1 2 3 4 5 Agree* 6: I found the chairs very cumbersome to use *Disagree 1 2 3 4 5 Agree*	Did you encounter any obstacles? If so, what obstacles did you encounter? Did it influence the way your drive the chairs? ____________ ____________ ____________ ____________
Section 3: Enjoyability	
Rate the chairs by circling the best descriptors for each of the following: I liked interacting with the chairs *Disagree 1 2 3 4 5 Agree* My interaction with the chairs was pleasant *Disagree 1 2 3 4 5 Agree* My interaction with the chairs was unnecessarily complex *Disagree 1 2 3 4 5 Agree*	Was there anything positive or negative that happened? Please describe it. Did it influence the way you controlled the chairs? If so, how? ____________ ____________ ____________ ____________

Appendix B: Evaluation Experiment Questions

B.1 EVALUATION SEMI-STRUCTURED INTERVIEW

After all trials, during the final interview the following questions were asked verbally by Study Conductor potentially in any order:

- Any first thoughts? Observations you'd like to share?
- How do you think the birthday party went? (functionality/experience)
- Did you have a favorite trial? If so, tell me about it.
- What was your experience like using the tele-presence interface?
- What was your most favorite feature? Least favorite?
- Tell me about how you made your rating choices in the survey
- What future uses can you imagine for such a system?
- Any recommendations of features we should add, delete, or modify?

Appendix C: Evaluation Survey Questions

After each trial, participants were emailed a link to a Google Survey with the following questions. A PDF printout of that website is provided over the next three pages.

ChairBot Post-Trial Survey

Fill this form after completing one task in the experiment.
When filling this form out, only reflect on the task you just completed.

Please ask the study personnel if you have any questions about the survey.

Sign in to Google to save your progress. Learn more

* Required

1. Describe how you arranged the furniture. What were your motivations? *

Your answer

2. Mark the answers below that best describe your experience.

The chair-arrangement task was {demanding, easy} *

	1	2	3	4	5	6	7	
Demanding	○	○	○	○	○	○	○	Easy

The chair-arrangement task was {complex, simple} *

	1	2	3	4	5	6	7	
Complex	○	○	○	○	○	○	○	Simple

During the trial, I felt {stressed, content} *

	1	2	3	4	5	6	7	
Stressed	○	○	○	○	○	○	○	Content

During the trial, I felt {annoyed, relaxed} *

	1	2	3	4	5	6	7	
Annoyed	○	○	○	○	○	○	○	Relaxed

3. State your agreement or disagreement with the following statements.

I was pleased with the final robot formation. *

	1	2	3	4	5	6	7	
Strongly disagree	○	○	○	○	○	○	○	Strongly agree

I was able to achieve the furniture arrangement I wanted. *

	1	2	3	4	5	6	7	
Strongly disagree	○	○	○	○	○	○	○	Strongly agree

I was successful in performing the arrangement task. *

	1	2	3	4	5	6	7	
Strongly disagree	○	○	○	○	○	○	○	Strongly agree

4. What did you think of this version of the interface? *

Your answer

(optional) Any other comments or explanations of the above answers?

Your answer

Page 1 of 1

Submit Clear form

Appendix D: Models of Implemented Command Abstractions

The following figures illustrate examples of how some of the command abstractions apply to the model shown in Figure 2.1. They are the command abstractions and associated affordances used in the evaluation experiment of Chapter 5.

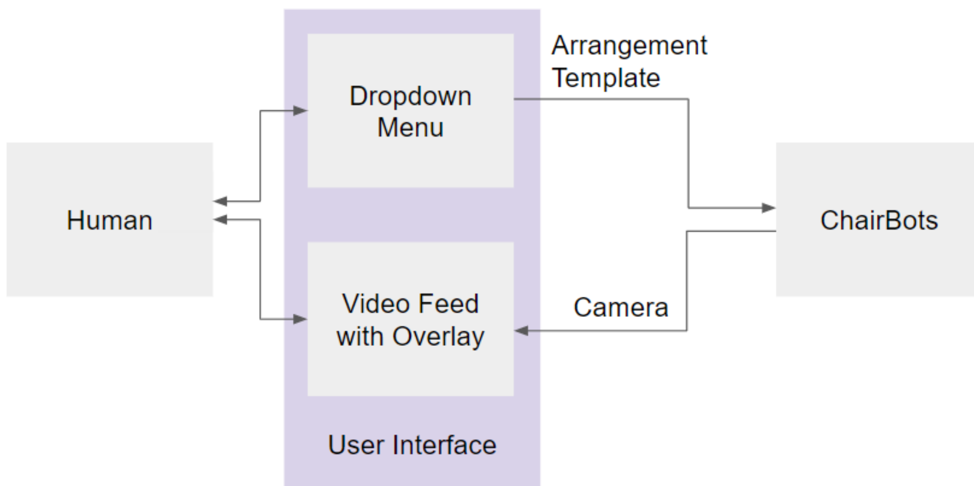


Figure D.1: The arrangement template command and affordance. An arrangement template is selected from a dropdown menu and then sent to the robot system which moves multiple ChairBots into their designated positions.

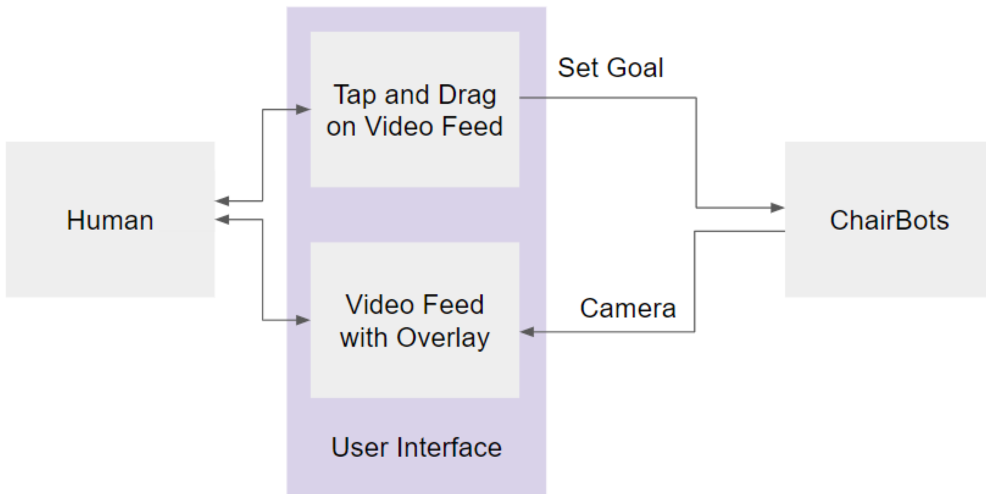


Figure D.2: The set goal command and affordance. A goal location is set by the user pressing down where they want the ChairBot to go and dragging to the orientation they want the ChairBot to face. This information is sent to the robotic system which then autonomously moves that ChairBot into position.

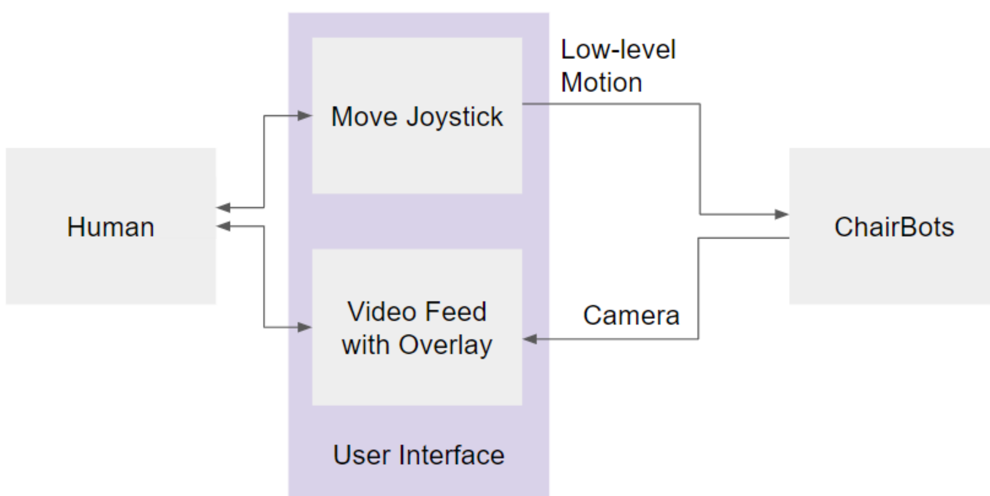


Figure D.3: Direct low-level motion command and affordance. The user can move a joystick to send a low-level motion command to a ChairBot which will move for as long as it is held out of its center resting position.

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