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Towards User-Centric Robot Furniture Arrangement

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Abstract— **Imbuing furniture with robot properties reduces the physical labor and time needed for arranging spaces, such as homes, classrooms, and offices. Outsourcing labor tasks to robot furniture requires users' involvement with functional user interfaces. We performed a user study on multi-robot furniture and added additional features based on the study results. The study involved 12 participants rearranging multiple non-robotic and robotic chairs (ChairBots). Results from the video and interview analysis revealed five high-level features missing in the original ChairBot: dual screen-based user interface, the ability to save and to set arrangements, the ability to move in multi-robot formations, the ability to snap to angles/gridlines, and higher movement precision. The improved system allows users to control multiple furniture robots, both locally and remotely. Such improvement sets the baseline functionalities of robot furniture arrangement systems while extending the potential utilization of established robotic chairs.**

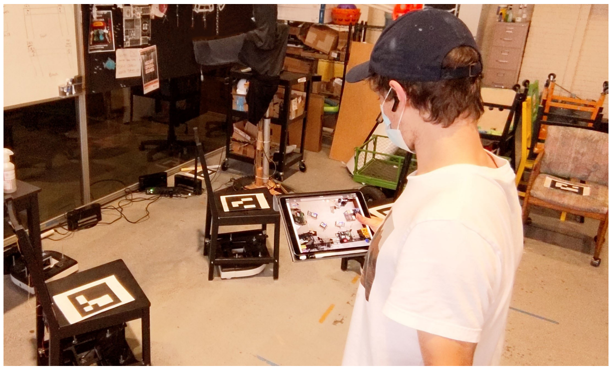

Fig. 1: This paper presents an experimental study and the resulting technology improvements based on participants' ratings and perspectives. The figure features the robotics chairs and the mobile teleoperation UI for controlling them.

I. 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 could 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 of robotic furniture demonstrate the feasibility of developing robotics further [1], [2], [3] and its ability to interact with people in shared spaces during collaborative arrangements [4], [5]. Additional demonstrations of robotic chairs have demonstrated the feasibility of commanding many chairs at once [6]; thus, this paper studies the user interface requirements of multi-robot furniture behaviors. We present the work in two phases: (1) a user study, and (2) technology improvements of the interface and control system.

First, we conducted a study on user interaction with multiple robot chairs using the original ChairBot system. We asked the participants to rearrange multiple non-robotic and robotic chairs in the same environment to answer: *(1)Where do people want robot chairs? (2)What do people think of the ChairBot? and (3)What are the controlling methods, arranging behaviors, and technical requirements of automated robotic furniture?* The results showed five high-level features missing in the original ChairBot system: *dual screen-based user interface, the ability to save and to set arrangements, the ability to move into multi-robot formations, the ability to snap-to-angles/gridlines, and higher movement precision.*

Second, we improved the system, drawing on the results from the user study. We especially developed force-sensitive resistors as physical sensors on the chairs and a mobile control (Fig. 1) for local and remote operation. We also added domain-specific semi-autonomous features such as remembering particular formations that were the user preferences and recognition of the environment.

This study's primary contribution is to set up the foundation for reliable multi-robot furniture systems, thus enabling future human-robot interaction studies 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 [7].

In the following sections we outline related work in robotic furniture, user centred design, and multi-robot interfaces (Section. II). Next, we present the baseline ChairBot platform upon which this work is based, which could be controlled locally via touch sensors, but had no autonomy features at the start of the research(Section. III). To generate better understanding of what features people want from robotic

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furniture, Section. IV outlines the methods and outcomes of the user study, including user ratings, behaviors, and feature suggestions across the study variables. After that, Section. V describes how the study's results led to our revised ChairBot interface controller design, followed by a discussion of future potential (Section. VI) and conclusions (Section. VII).

II. RELATED WORK

Utility of Robotic Furniture: Prior work in robot furniture design ranges from functional to artistic and has considered the robotization of everyday objects from wheelchairs [8] to couches [9], ottomans [4] to trashcans [10], [11], [12]. These examples have demonstrated that people can interpret motion-based communications of robot furniture in a way that enables them to rearrange around people, evoke playful or useful interactions, and otherwise shift between physical element of the room and social character as needed by the application [13], [14]. This work, however, integrates user perspectives into the design of a user-in-the-loop multi-ChairBot control system.

Prior Uses of User Centred Design to Design Technical Systems: The ChairBots project adopts a User Center Design approach at which end users are active agents within the iterative design process [15], [16]. Along with the empirical assessment of effectiveness, end users' involvement is required to develop a joint sitting at which their needs and tasks impact technology development. Iteratively, end users try out and evaluate working prototypes, so each evaluation informs the redesign of the next prototype (i.e., modalities and functionalities) and user requirements in a continuous user research [17]. 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 [18], [19], [17]. 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.

Unique Challenges of Multi-Robot User Interfaces: While this paper focuses on a multi-robot control system that operates in a human context, i.e., its intended use is in a shared space in which the robot can rearrange around people, our approach to multi-robot control also benefits from previous work in generalized multi-robot control [20], [21], [22], [23]. As the number of controlled robots in a system increases, so does the operator's required cognitive load for accomplishing similar tasks [24]. Such user interfaces need to be specially designed for this task [25] and often incorporate abstracted, sometimes intelligent, autonomous features in order to reduce the cognitive load of their human operators [26]. Such controllers can also reduce cognitive load by specifically integrating the needs of the application for which the robot is used [25].

III. THE CHAIRBOT

The used robotics platform, here forward **ChairBots**, was established by Knight et al. as a cost-effective platform to study the use of expressive motions and non-verbal behaviors

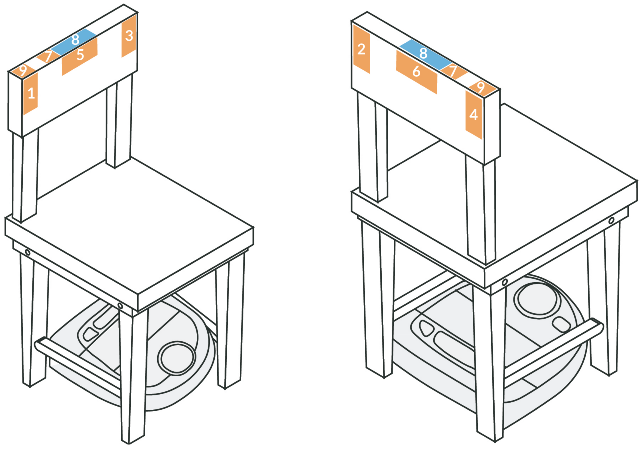


Fig. 2: Schematic diagram of a ChairBot with 6 adhered touch sensors. **1,2:** Turn Left, **3,4:** Turn Right, **5:** Go Backward, **6:** Go Forward, **7:** Turn the robot On/Off, **8:** LED indicator, and 9: Turn All robots On/Off

to communicate robots' intentions and evoke human responses in social spaces [7], [5]. 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[7], [27]. 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. [7][5]

Later, Knight et al. introduced the touch sensors to the ChairBots as an end-user interface, so participants can adjust the robots' motions as if they were interacting with chairs on casters [1], [2]. The touch sensors enable participants to control the chair locally by touching it to go forward, backward, and rotate in place. Figure. 2 shows the ChairBots version we are using and the locations and motions associated with each sensor. Also, we set up the ChairBots to allow participants to send the same motion command to one or several robots.

	Non-Robotic	Robotics Chairs
Empty Space	N=5	N=7
Around Table	N=7	N=5

TABLE I: We recruited participants and divided them between two independent variables (chair type and space type)

IV. EMPIRICAL STUDY

The study aims to understand the potentials and current limitations of the ChairBots as a platform for furniture arrangement. In particular, we structured our study to answer three research questions: Where do people want robot chairs? What do people think of the ChairBot? and What are the controlling methods, arranging behaviors, and technical requirements of automated robotic furniture?

A. Methodology

We conducted a 2x2 mixed study for 12 participants to arrange both robotic and non-robotic chairs around either an empty space and/or a table. The participant's ages (18 - 35)

	Category	Data Source	Data Type	Definition
RQ1	Use-Cases	Interview & Video	Verbalization	Situations in which robotics furniture could be used
	Contexts	Interview & Video	Verbalization	Circumstances in which robotics furniture could 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 II: The 9 categories of data we collected as dependent variables, sorted by research question.

and gender varied (six males, five females, and one gender non-conforming). We had two counterbalanced independent variables (Table. I). The first independent variable was chair type, with robotic chairs being ChairBots (Section.III) and non-robotic chair type being the same model of chairs on casters. The other independent variable dictated the space around which the participants arranged the chairs: two preset tables or an empty space. The order in which a user interacted with the chair types varied for each user such that half interacted with the Robotic chairs first. Using a 1-5 Likert scale (1=None and 5=Expert), only one participant identified himself as an expert with robots while the majority described themselves as novices (M=2.58, SD=1.31).

The study procedure was approved by the university ethics research board, consisting of a consent form, orientation to the speak aloud protocol and 2 chair arrangement sessions corresponding to the study conditions. For each session, we gave participants a set of 3 chairs followed by a scripted tutorial to demonstrate the relevant chair type's functionality. Since we would be asking participants to think aloud by expressing their thoughts and reactions verbally, before their first session an warm-up exercise with the users was conducted. To model the Thinking Aloud Protocol (also known as concurrent verbalization), we practiced by talking through estimating how many windows are in their house.

During the experiment, we collected a variety of data. Implicit data (i.e., participants' actions that they did not say explicitly, but rather were gathered through analysis of the videos) was collected by video-recorded the study area using two cameras in an overhead and from the corner view. Explicit data was also collected via five-point Likert scale surveys asking participants to rate the non-robotic and robotic chairs in terms of mobility, usability, and enjoyability. We also collected additional explicit data at the end of the participant's second session via a reflective interview with the participant. This semi-structured interview focused on participants' expectations of robot furniture to prompt ideas about suitable implementations.

We 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.II), to conclude the work.

B. The Impact of the Study Variables

In this section we report on how the study 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. 3a). 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. 3b). 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) should 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. 3c). On the other hand, they preferred normal chairs for offices, schools, and meetings. Since robotic furniture could conceivable encompass endless categories, we also coded for use-cases of other types of robot 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.3e 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 because they anticipated the mobility limitations of the robots. This data suggest that future robot furniture systems should allow for a range of participant setup styles.

C. *User-Desired Features*

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 robot furniture is to make arrangements that people will use, thus many participants expressed the desire to save 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 involved being able to move relative to the motion of the other Chairbots. Observation of the study videos showed that participants found the lack of geometric intuition in the system quite frustrating.

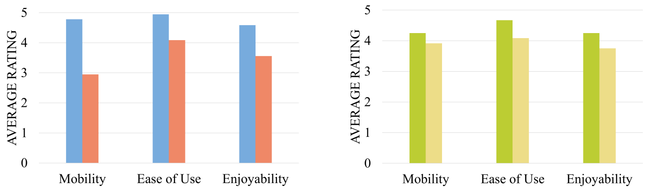
Improved motion control precision: Finally, users expressed frustration that they were not able to move the robots at variable velocities. 75% of the participants reported overshooting via the speak aloud protocol. This issue refers to the precision of the robots' motions especially in terms of truing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

V. TECHNOLOGY ADDITIONS AND CHANGES BASED ON STUDY RESULTS

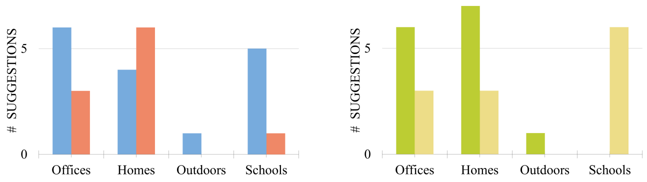
Our experiment offered insights about improving the existing ChairBot and highlighted the need for application-based software features specifically useful to rearranging robot furniture. We equipped the baseline ChairBot with two significant additions: a screen-based user interface and autonomous motion. This section describes the motivation, and implementation of five technology targets derived from participatory design 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**

The implementation of these features required substantial extensions to the baseline system (described in Sec. III) that advance the ability of robot furniture arrangement to function as an application:

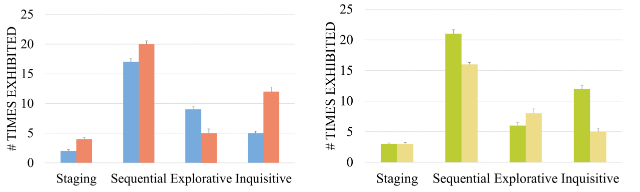
- A Screen User Interface (UI) was implemented on both mobile, and desktop to control ChairBots and trigger



(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

Fig. 3: Results from the empirical study. 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.

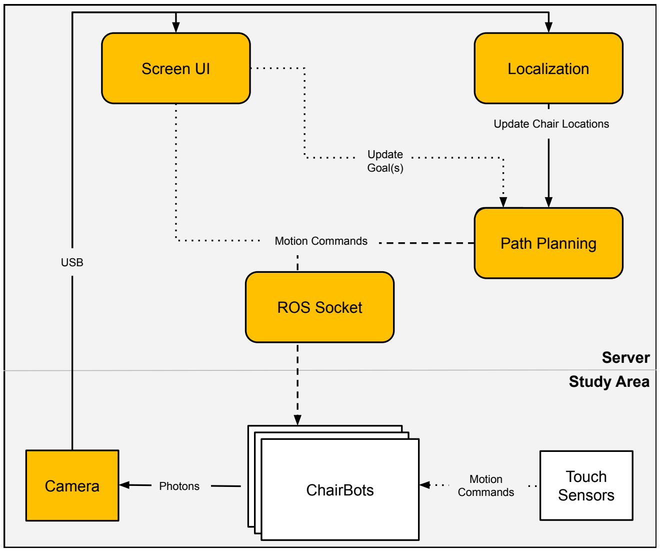


Fig. 4: Diagram showing key modules of the system with changes highlighted. This final architecture enables features identified during the study. The new modules were added to enable features discovered during testing and survey. Original modules include modules used during the experiment. Modules with rounded corners represent modules that exist primarily as software, whereas abrupt corners represent modules with a physical presence in the study area or scene. The arrows represent Autonomous ———, Semi-Auto , and User Driven ....

You are driving:
Chair2, Chair3,

☐ Chair1
☑ Chair2
☑ Chair3
☐ Chair4
☐ Select All

Fig. 5: Screenshot of the added screen-based user interface on being run on a personal computer.

autonomous action.

- An overhead camera was added which gives a top-down view of the ChairBots. This streaming video over USB to the server where it is displayed on the UI and used as the primary sensor for 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, provide the enabling technology to support the user-study inspired features presented in the subsections that follow.

A. Dual Interface

This subsection describes how the motivation and design of the screen-based user interface (UI), 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 thought the screen-based user interface (UI) could include additional features related to memory or precise control. This UI replicates the functionality of the physical controller, and also supports the computation features introduced in the rest of the section.

We implemented the screen UI as a a webpage with a responsive front end that was accessible on a range of screen sizes: including mobile and desktop, as suggested by the study participants. In order to make this web-based controller work on a robot furniture operator’s smartphone, it was deployed on a backend server which could serve and communicate with the webpage from any device on its local network.

In the UI, four spaces were allocated with different purposes: selecting active ChairBots, directly controlling motion, enabling autonomous motion (snap-to-grid, formations, and arrangements), and viewing the scene (Fig. 5): (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 as one could anticipate collisions. 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 controlling method are included in the following sections.

B. 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 would be 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 UI. When pressed, a popup would appear prompting the user to name the arrangement, giving it an identifier that is displayed during **set**. The arrangement, name and coordinates, would 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 UI 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

```
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

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

C. 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. In our participatory design 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 UI (Section V-A) commands and expanding the autonomous arrangement system (Section V-B). 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 update allows for a single user to move several ChairBots.

Algorithm 3 Algorithm to Update Goals to Move in Formation

```
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 $goalAngle_i, goalCoord_i$
```

D. Integrating Geometric Knowledge of Space

During the participatory design study, users expressed an expectation that the chairs would have geometric knowledge of the room. For example, it is common for people to arrange furniture relative to the walls of the space or existing furniture. Thus, 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 4 Algorithm to Update Goals for Snap-to-Geometry

```
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 robot chairs should understand the geometry of the room and that furniture arrangement is often organized relative to both the room and each other.

E. Meeting User Expectations of Precision

A second result from the study 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 would slow down the ChairBot.

Improving the Motion Precision: While the original software implementation was calibrated to rotate the chair at five degree increments, participants could perceive the difference between 45 degrees and 50. Thus, we updated the unit of motion to one degree. This underscores the attention to geometry that users might have in controlling future robot 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. In the physical interface, we replaced the capacitive contact sensors 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). 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.

VI. DISCUSSION

The simple design of this platform (an IKEA chair, a Neato Botvac, and connecting hardware) and the software described in this paper for its human-in-the-loop arrangement and motion control are intended to ease reuse by other researchers, enabling future research in robot furniture applications, user-centric robot control interfaces, and/or efforts to increase the autonomy and social intelligence of simple robots.

Our empirical study helped surface user expectations of how robot furniture should behave, augment user control with intelligent features, and update the ways in which it is commanded. Learning about participant expectations of robot furniture revealed flexible user perspectives about when robot furniture systems should be used: like moving out of the way so one could 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 robot furniture system.

Finally, we advance a low-cost research platform that we hope to enable future research studies: 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. Continued developments of this technology include integration of intelligence into customized robot furniture interactions, and integration of social interaction intelligence into future ChairBot application development, e.g, the creation of a ChairBot cafe. Both offer opportunities to consider multi-robot/multi-human social interaction.

VII. CONCLUSION

The goal of this work was to design an effective human-in-the-loop robot furniture system in which a user can effectively arrange a group of ChairBots, e.g., for a meeting or an event. To achieve this system, we began with a baseline design for a person to control one or more ChairBots via a physical interface. Next, we conducted an empirical study to assess this design, and elicit the features users desired for a robot furniture system. Building on these results, we expanded our control interface to offer both screen and on-chair physical controllers. We also implemented identified system features related to saving and setting particular arrangements utilizing autonomous robot motion, and augmented human-in-the-loop control that leverage the geometries of the space.

This is novel relative to prior implementations of robot furniture using non-abstracted controls (i.e., moving one chair at a time with a user in the loop) because now robot furniture controllers can effectively command and control multiple robot furniture robots at a time, drastically decreasing the labor required for one human to rearrange the furniture in a space. By melding autonomous arrangements with and empirical study to explore early impressions of this system, we were able to collect initial user impressions of multi-robot furniture systems.

Expanding upon the baseline physical robot system and touch-based on-robot control interface, we integrate study 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 create a screen-based interface to offer similar 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.

In the future, we will continue exploring the design of muti-robot, muti-human interactions while showcasing the iterative nature of the human-centered design. The design of our robots would benefit from additional user studies that assess how the end-users perceive the changes introduced in this work. Perhaps a full UCD iteration could influence the usability and functionality of the ChairBots mobile and physical UIs.

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, ultimately robot furniture is created to support the needs of the people who intend to sit on them.

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