Touch and Toys

new techniques for interaction with a remote group of robots

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ABSTRACT
Interaction with a remote team of robots in real time is a difficult human-robot interaction (HRI) problem exacerbated by the complications of unpredictable real-world environments, with solutions often resorting to a larger-than-desirable ratio of operators to robots. We present two innovative interfaces that allow a single operator to interact with a group of remote robots. Using a tabletop computer the user can configure and manipulate groups of robots directly by either using their fingers (touch) or by manipulating a set of physical toys (tangible user interfaces). We recruited participants to partake in a user study that required them to interact with a small group of remote robots in simple tasks, and present our findings as a set of design considerations.

ACM Classification Keywords
H.5.2 Information interfaces and presentation: User Interfaces—*Graphical user interfaces (GUI), Interaction styles, Theory and methods*

Author Keywords
human-robot interaction, tangible user interfaces, touch interfaces, tabletop computing, robot teams

INTRODUCTION
Interaction with a team of remote robots is emerging as an important problem in several key application areas such as Explosive Ordnance Disposal (EOD), urban search and rescue (USAR), high-risk and remote exploration, military, and surveillance. However, real-time interaction with a remote group of robots is a difficult problem. The physical world presents unpredictable and complex variables, such that robots cannot be relied on to move and act exactly as commanded or expected. An operator of a remote robot needs to have a strong HRI *awareness* [5] of robot progress and state, and an intuitive interface to maintain effective control.

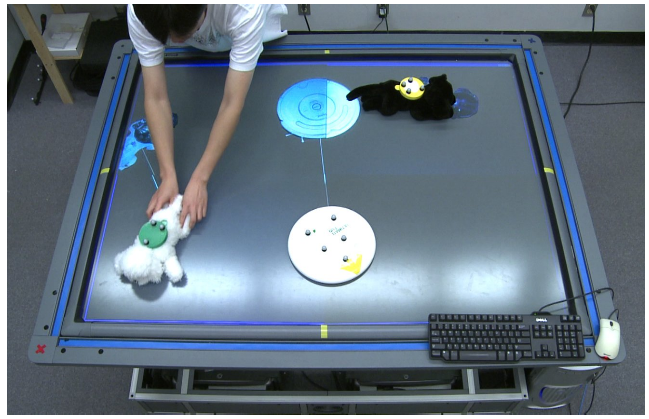


Figure 1. A user interacting with a remote group of robots using our toy interface.

These challenges are magnified when interacting with a team of (often heterogeneous) robots, often resulting in high *human-robot ratios* [38] where several collaborating users are required for each robot.

In contrast to low-level interfaces where users micro-manage robot morphology, motors, cameras, etc., the domain of Human Robot Interaction (HRI) is pursuing interaction paradigms that support high-level interaction with robots that have some autonomy over their low-level sensors and actuators. In such interfaces, an operator is only required to give high-level commands such as simple locomotion and way-point directives. Improvements in these interfaces ultimately reduce the number of operators required and allow users to focus on higher-level mission and task details and less on controlling the robots. With teams, higher-level interfaces enable users to focus more on the relationships among the robots than on individual robots, such as where each robot is located in relation to others in the team.

We believe that the HRI design space is still fairly unexplored, and when it comes to interaction between a single user and a group of robotic teammates, there is not yet a base or standard for the creation and design of interfaces. Therefore, we take an exploratory approach in search of innovative solutions to this interaction problem that may prove to offer fundamental advantages over existing solutions. Specifically, we present two novel tabletop computer interfaces, one using touch input and another using tangible user interfaces (TUIs) (shown in Figures 1, 4), and a user study that explores how these interfaces fared for interaction with a remote group of robots in a set of simple tasks. In particular, we focus on the spatial organization, movement, and location of the robot group. As far as we know, this is one of the very first attempts to design effective tabletop, TUI, and touch interfaces for real-time interaction between a single user and a group of remote robots.

We intentionally avoid the question of solving specific problems and tasks and instead look explicitly at user interaction. That is, how do users perceive and respond to touch and TUI-based interfaces, and how do they use them for interacting with a group of heterogeneous robots? This premise follows precedent (e. g. [18, 23]) – we use in-lab simulations that focus on the interaction experience rather than task validity – placing the validity of our work in how it informs the design of real-world interfaces across a wide range of group HRI tasks.

Tabletop computers are horizontal interactive displays that resemble a traditional table, often allowing users to directly interact using touch or a pen interface. Tabletops are emerging as a commercially vialable alternative to the desktop; their large, public workspace surface provides a unique interaction environment that emphasizes collaboration, planning, organizing, and other spatially-situated activities [19, 27, 28], characteristics well-suited to the task of controlling a team of robots.

Tangible user interfaces (TUIs), or graspable user interfaces [7], leverage the fact that humans are naturally adept at using physical real-world objects. TUIs aim for the "seamless coupling of everyday graspable objects (e. g., cards, models)" with associated digital information [14]. This couples the action and perception spaces, offering gains such as immediate physical feedback that are not possible with traditional interfaces [6, 7, 14, 31].

A common approach in previous work maps physical TUIs (e. g., a *brick* [7]) to digital objects (e. g., a PC on-screen window). TUIs can also map to an external physical prop, hiding most of the digital intermediaries. By mimicking the object's physical properties, careful TUI-object coupling can strengthen the spatial and action mapping between the input and the object, unifying input and output spaces and enabling the user to perceive and act at the same place and time [1, 31].

In this paper, we map TUI and touch interfaces to HRI tasks involving robot groups. We present two interface implementations, toy and touch-based, which enable a single user to interact with a team of robots. We use exploratory user evaluation to provide external viewpoints on our interfaces, building a stronger understanding of how our techniques map to the larger HRI problem.

RELATED WORK

Designing robotic interfaces that couple intuitive interaction with accessible awareness feedback is a strong theme in HRI, commonly focusing on high-level interaction, frameworks and taxonomies [5, 10, 16, 36, 38].

Social robotics is an approach to HRI where robots communicate using human language and cues. The benefit of this approach is that users are not required to understand the technical language of the robot [2]. A robot can express its state using social cues [4, 20, 40, 41] or similarly accept commands using techniques such as gesture, voice, and social-reference recognition [9, 20, 33]. These techniques, however, often do not map well to the real-time, dynamic, precise spatial control of the formation or location of robot groups. Further, other complications exist for remote robots such as robot selection (who to interact with, remote gesturing and group awareness, both still open problems even for human-human communication).

Another approach to HRI design is inspired by computer games [25]. For example, a human-robot interface can be designed to support interaction with multiple robots following a first-person game perspective [37], or a strategy-game-like layout [15]. One limitation of these existing systems is that the traditional interface forces a mapping through the keyboard, mouse, and display interface.

Using TUIs for HRI is still a new and fairly unexplored interaction concept. Early work used a sensor-loaded TUI-like model of an airplane to control the roll and pitch of a small simulated unmanned aerial vehicle (UAV) [23]. Other existing systems include one that used a simple, generic TUI implemented using the Nintendo Wiimote to navigate a robot and to control its morphology using gestures [12], and another that used an adjustable-height TUI to interact with a group of robots in three-dimensional space using a stylus and a tabletop computerized surface [18]. Perhaps the ultimate TUI for controlling a robot is the robot itself. Some projects [8, 24] enable users to directly manipulate the robot to teach or demonstrate movements. Similarly, a robot can be remote controlled by coupling a pair of distant robots, where moving one manually forces the remote robot to move in tandem [32]. However, as far as we know we are the first to design a TUI interaction approach that moves beyond a single robot to accomodate a remote group of robots.

Several projects use sketch or stylus interfaces for robot control [30, 34], for tasks such as path planning and high-level direction. However, these interfaces were confined to a small tablet with stylus-based interaction, using a single stylus with one or more robots. Our interaction techniques support two-hand interaction and many (inputs) to many (robots) mappings, which we believe are important for interacting with multiple robots. Moreover, our large table surface and physical TUIs help to emphasize the spatiality of the real-world robot arrangements [19, 27, 28].

The idea of using tabletop computers for robot interaction is not completely new, where the table has been used as a platform to control robots [26, 29] or hypothetically train them [39]. We continue this work and use the tabletop as a platform that enables us to utilize multi-hand, spatially oriented TUIs and touch.

Using TUIs and touch for robot interfaces is a new concept with very little (or no) work in the field and there is very little specific design insight. As far as we know, our work is the first attempt to design and evaluate user interfaces for robotic groups that will take advantage of the unique characteristics of large tabletop displays, TUIs and touch interfaces.

INTERFACE DESIGN

We present two tabletop interfaces for interaction with a remote group of robots, one using touch and another using TUIs. The tabletop PC is a standard PC with four video outputs combined to form a high-resolution (2800 x 2100 pixel) display projected onto a 146 cm x 110 cm 2-touch DViT SMART™ touch-sensitive board. The TUI interface uses a Vicon object-tracking camera system to track the location and orientation of the TUIs on the tabletop surface (see Figure 2(a)). A second Vicon system tracks the robots and reports back to the controlling PC, which commands the robots via 802.11 wireless and bluetooth (see Figure 2(b)). We use Sony AIBO Robotic dogs (one white one black) and an iRobot Roomba as our robots.

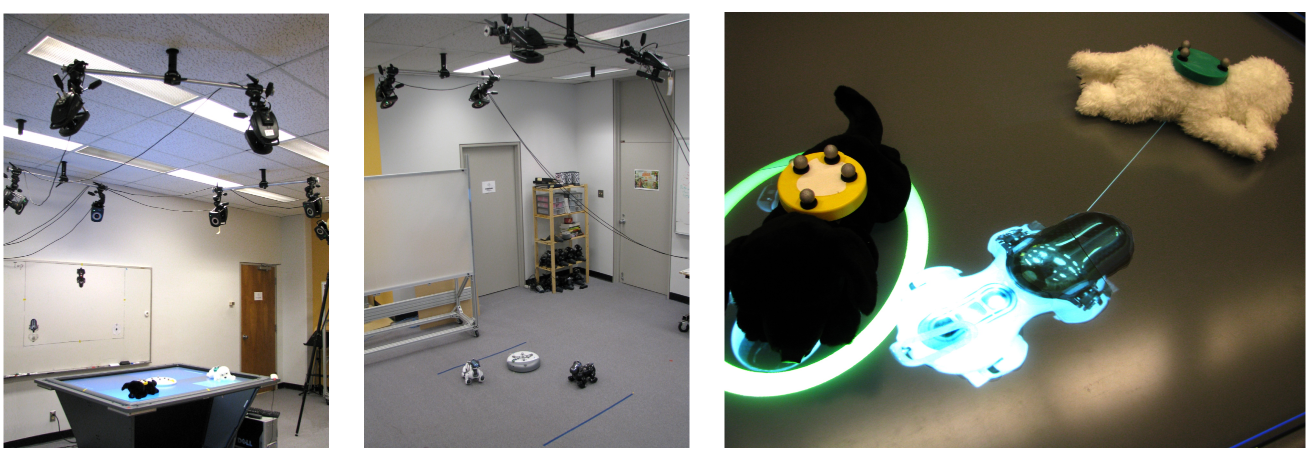
We specifically selected the large tabletop, TUIs, and touch technologies to leverage the physical and spatial nature of the robots. Following, we designed the interface to be intuitive and spatial in nature, enabling and encouraging users to utilize both hands simultaneously.

The basic design of our interfaces enables the user to specify a target location and orientation for a given robot, with the system showing the user the actual current robot location. The target location is represented by an interactive icon in the touch case, or a physical toy object in the TUI case, and a line is drawn from the current location to the target to specify the robot's planned movement trajectory. The *path-finding* algorithm employed is a simple three-step process: once a target is specified by the user, the robot first rotates itself to face toward the target location, it then attempts to walk straight toward the target, and once it reaches the target location it finally rotates to the target orientation. When the physical robot has reached the target location, the target icon or TUI is highlighted by a green halo (Figure 2(c)).

This simple, limited algorithm was deliberately chosen for several reasons. First, given the simplicity of the task, we wanted to force the users to navigate the robots on a scale more involved than simply providing waypoints. Rather than enabling the computer to make optimal navigation decisions, this approach keeps the user involved and creates the possibility of robots colliding during navigation. The possibility of collisions, in turn, requires users to pay close attention to the interface and various HRI awareness-providing mechanisms [5]. This design provides the possibility of error and encourages user engagement and dynamic user interaction.

Tangible User Interface

Our goal is to enable users to intuitively associate a given TUI to a particular robot and to naturally know how to move and use the TUI without training. We used



(a) The tabletop workspace with the TUIs on top and the Vicon ceiling setup.

(b) The robot workspace with Vicon cameras and robots.

(c) The TUI interface. The green halo around the black dog means the black AIBO has reached its target. The white AIBO icon represents the physical robot's location, attempting to follow the line toward the target location defined by the white-dog toy.

Figure 2. Interface overview

plushie dogs, black and white, to respectively represent the AIBOs, and a white Frisbee to represent the white Roomba (Figure 3). Moving and rotating these TUIs is as intuitive to a user as any physical object, and the spatial mapping between the TUI state and the robots is direct. The plush-and-toy design of the TUIs makes the them familiar, a pleasure to touch and fun to use, important aesthetic points that we believe improves the experience of using the TUIs. Also, the use of simple TUIs lowers the importance of the TUI design as a variable, and helps us focus on the more general topic of a user using a TUI.

We carefully selected the size of the TUIs to be similar to the actual robots and the dimensions of the physical robot space to match the tabletop, providing physical constraints to interaction. This enables users to rely on the intuition provided by the TUI dimensions, for example, two robots cannot be placed at the same location because the TUIs collide. This provides a physical constraint to the interface that reflects the real constraints of the remote robots.

Touch Interface

We selected a very simplistic touch interface where each robot is represented by a single icon. To move the icon, the user could either translate it by touching the center circle of the icon and moving it, or by selecting outside the circle and using RNT (Rotate'N Translate) a technique that enables the user to rotate and translate the object simultaneously using only a single touch point of input [17, 13](Figure 4).

EVALUATION

A core problem with evaluating human-robot interfaces generally, and interfaces for a group of robots specifically, is validity. People who interact with groups of robots in practice will conceivably be trained professionals dealing with real, meaningful tasks. Unfortunately, real world robotic-group users who are engaged with real tasks are very rare and often inaccessible, and simulating valid in-lab scenarios with limited off-the-shelf robotic technology can be very difficult.

We explicitly avoid this problem by focusing on the interface itself rather than the application of the interface to a task. We want to evaluate directly how people approach, respond to, and use the interfaces that we have created. While the dynamics of interaction will change with the task and training of professional operators, we feel that many of the basic interface principles and gains, the *visceral* level of interaction [21] and many usability principles of the interface itself, will remain the same. We approach the evaluation of our system with primarily qualitative techniques.

Qualitative Evaluation

Our evaluation approach is primarily qualitative, where we aim to describe and understand the dynamics surrounding the user's interaction experience. This contrasts sharply with more traditional quantitative approaches, where task-completion time and direct user efficiency are the primary concern. In this work, we take the stance that quantitative evaluation only provides a limited understanding of user experience: perfect understanding is impossible and results are always open to interpretation [11, 35].

Qualitative evaluation fits well with our non-task focus and our general exploratory approach. At this stage in the maturity of the technologies we use, the qualitative description resulting from our study is more useful than measuring performance of some arbitrary task. By exploring the dynamics of how users interact with our

Figure 3. Our tangible user interfaces and corresponding robots

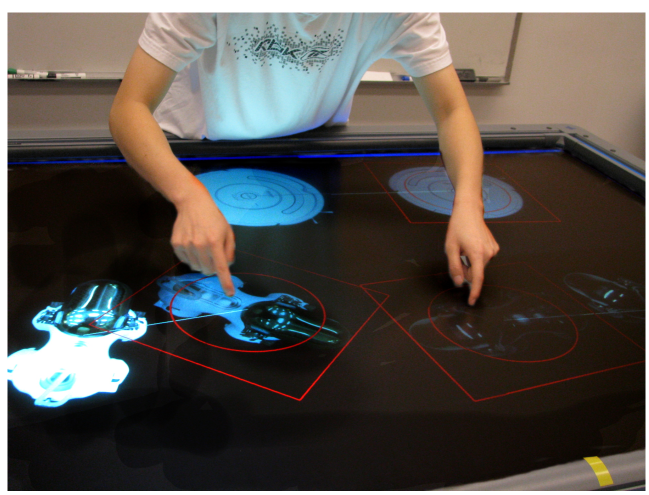


Figure 4. A user simultaneously interacting with two robots. Touching inside the circle does a translate, touching outside the circle (but inside the square) performs an RNT operation.

interface at a higher level, we provide insight that can aid designers to get the "right design" before trying to get the "design right" [11].

Experimental Design

We recruited 23 participants, aged 19–47 yrs (avg 25.5 yrs, SD 6.5 yrs), 15 male and 8 female, from the university population to participate in our study. Each participant was paid $10 per hour for their time (most took 1.5 hours and were paid $15). 20 were right handed, 1 left handed and 2 ambidextrous.

Throughout the experiment, we presented the user with a robot configuration using cut-out robot pictures on a white board. After which, the user was asked to put the robots into the configuration and locations that we presented to them (Figure 5). This was done in three stages, a one-robot, two-robot, and three-robot stage.

For each stage, the users were asked to move the robots from a starting position to five configurations using both the touch and the toy interfaces in turn. The configurations were the same across interfaces, but changed with the number of robots. For the one-robot case, the user did the task for each the AIBO and the Roomba, for the two-robot case we used a single AIBO (white) and a Roomba, and for the three-robot case we used two AIBOs (one black, one white) and a Roomba. The order that we presented the touch and toy interfaces, and the order that the robots were presented in the one-robot case were counterbalanced across users, but all users were presented with the one, two, and three-robot cases in order. The user completed questionnaires before the study, after each stage and interface type, post-study, and then to go through a final interview.

RESULTS AND ANALYSIS

Users unanimously reported (100%) the graphical feedback on the table easy to understand and that it was not

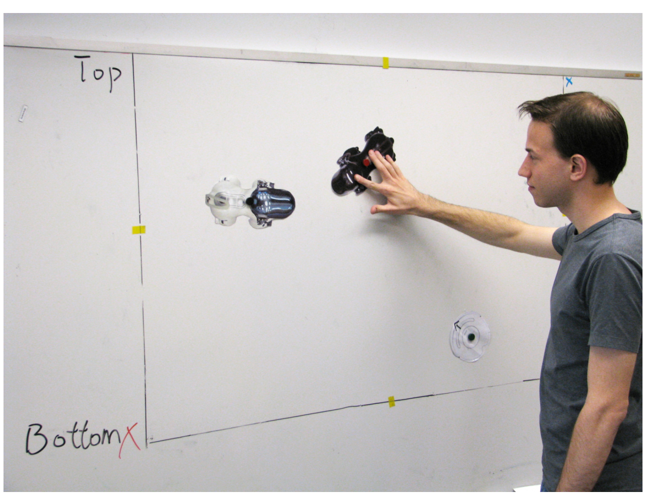


Figure 5. A study administrator presenting a target robot configuration to a participant.

unnecessary, and we found no correlation between the sex, age, handedness, or past experience of the participant and their reaction to the system. In the one-robot case, we found no statistical difference between how the user used or thought about the Roomba or the AIBO. Finally, while there were some statistical differences in time efficiency (as explained below), we found no consistent statistical difference between how long users took to complete the tasks based on the touch or the toy interface, only based on the number of robots (Table 1).

Task Completion Time

Statistical analysis was conducted on all our task-completion-time data. In the one-robot case, a 2×2 ANOVA (Technique: Toy, Touch $\times$ Robot: AIBO, Roomba) analysis revealed no significant Technique $\times$ Robot interaction ($F_{1,22} = 0.15$, $p = 0.7$), which suggests that performance with the techniques is not substantially influenced by the robot type. There was no significant main effect for Technique ($F_{1,22} = 0.54$, $p = 0.47$). However, there was a significant main effect for Robot ($F_{1,22} = 19.15$, $p < .01$), indicating that the task completion time for the Roomba ($M = 131.8s$, $SD = 10.34s$) was 11% faster than the AIBO ($M = 147.28s$, $SD = 21.43s$) on average. In the two-robot case, a paired-t test was conducted and it showed a significant difference between the touch and toy method ($t_{22} = 2.61$, $p = .02$). With the toy interface, the participants completed the task ($M = 170.26s$, $SD = 26.19s$) 10% faster than with the touch interface ($M = 188.22s$, $SD = 32.33s$). In the three-robot case, a paired-t test showed no significant difference between the two interaction methods ($t_{22} = 1.24$, $p = .23$).

Usability

We asked four ease-of-use questions (via questionnaire) after each interface type and across all three robot cases (6 times in total). The results are shown in Figure 6 which shows the percentage of positive responses (>4 on a 7 pt Likert) to each question respectively. On a finer granularity, when toy and touch received a similar amount of positive response, toy received significantly more *strongly positive* responses than touch. For example, responses to the "precise control over robot movement" question in Figure 6 look similar across cases, but the strongly positive responses for toy/touch were were 30%/7%, 30%/9%, 22%/9% for the one, two, and three-robot cases respectively.

		AVG	SD
1-robot	touch	138.3 s	16.2 s
	toy	140.7 s	20.5 s
2-robot	touch	188.2 s	32.3 s
	toy	170.2 s	26.1 s
3-robot	touch	265.0 s	43.9 s
	toy	256.2 s	42.9 s

Table 1. Average task completion time.

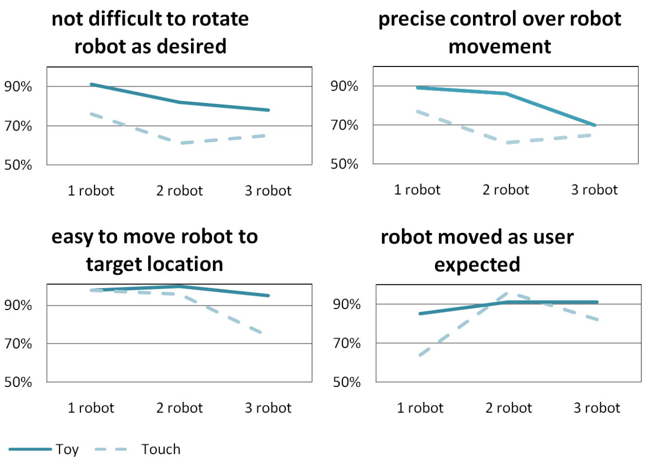


Figure 6. Percentage of *positive* ease-of-use responses.

Users reported that (in comparison to touch) the toy interface gives more precise control over robot movement, and makes it easier to move the robot to the target location and rotate the robot as required. Further, in the two-robot case users said it was not confusing to monitor the two robots at the same time (70% toy, 61% touch) but easy to control the robots simultaneously (78% toy, 57% touch). With the three robot case, users also said it was generally not confusing to monitor all three robots at once (70% toy, 52% touch) and that they found it easy to form the group formations asked (83% toy, 57% touch). Further, Table 3 reports the percentage of users that responded positively to questions about using both hands and controlling multiple robots simultaneously using the touch and toy interfaces. The table shows that users found it much easier to control two and three robots simultaneously with the toy interface than the touch interface.

Preference

For each of the one, two and three robot cases users were asked how much they preferred each interface (one user did not answer for the one and three-robot cases). The results, shown in Table 2, clearly show that people preferred the toy interface over the touch interface in the two and three robot case. This preference echoed in the written questionnaires and post-test interview as well. One user explained that the toys gave them a "sense that [they were] in contact with the robot," and seven participants wrote that they found it easier to visualize the robot position and orientation with the toy interface. One user reasoned that the toys provide more visual cues about the orientation and organization than the flat images used in the touch interface.

	1 robot	2 robot	3 robot
Toy	45%	83%	77%
Touch	45%	17%	14%
Neither	10%	0%	9%

Table 2. User-preferred interfaces for each robot case (percentage of users).

Touch

Users described the touch interface as being simpler due to less equipment and more precise and accurate due to the high resolution of the screen. Further, the touch was reported to be less intimidating because it was familiar and more similar to traditional PC interfaces. On the other hand, many people complained of the RNT scheme, with eleven users explicitly reporting that it was unintuitive to rotate the robot icon around the finger point. This is a property of RNT that users liked for ballistic movements but which caused problems for precise rotation of the robot once it was at the target location (this matches previous findings regarding RNT [17]). RNT rotation moves the center of the object, requiring a final corrective translation. Instead, users recommended that it would be more intuitive for the robot icon to rotate around the center, "spinning like a plate."

Finally, with the three-robot case a few users complained of visual clutter – 3 icons for the real robots, 3 icons for the robot-controlling widget, lines connecting them and the green halos crowd the interface. One participant complained that "for the touch interface, you have six pictures (displayed on the table). It becomes confusing (when they overlap on top of each other)."

Toy

Users reported that the toys "were tactile and seemed more realistic" with their three-dimensional nature, with seven users explicitly noting that with the toy it was "a lot easier to visualize what was happening [remotely]" and to visualize the robot configuration. Further, it helped make it "easier to understand the rotation" and other robot state, enabling them to "focus on collision avoidance."

The primary complaint (mentioned by several users) is that the reflective markers for the tracking system get in the way of grasp, where occluding the markers can make the system lose track of the toys and cause erroneous robot movements. Users reported that the marker areas become no-hands zones that distract users from the natural grasp-intuitiveness of the toy.

Robot Movements

Users reported through comments and feedback that the robots often moved unexpectedly, despite the contrary evidence shown in Figure 6, saying that it was often difficult to visualize the path that the robot would take and that the "robots seemed to take slightly different paths (than the one [users] planned)." The primary reason cited is that users expected the robots to copy or replay the movements given by the user, including sidesteps and exact paths, instead of moving directly toward a landmark target as the robots were programmed to do. This was explicitly described by ten of the users, and the problem was more prominent overall in the three-robot case and with the toy cases.

Another aspect of this was that the robots did not move consistently or in a straight line due to physical constraints and noise such as the robot mechanics and a somewhat uneven carpet. Because of this, robots sometimes had to correct their trajectory in mid-movement. Users further pointed out that our interfaces gave them no indication of the robot moving and rotation speed, or time to target location.

The robots have mechanical limitations and challenges with precise movements. As such, they sometimes had difficulties moving to the exact target location specified by the user, and are sometimes off by as much as 10 cm. When this happened it was very obvious and visible to the user and in the worst cases added considerable visual clutter.

With the toy interface, moving an object from one place to another was reported to be a trivial task by most participants. However, one participant said that "at times [she] forgot [she] was moving a robot and not only toys", such that she would "pick up the first one and put it [at the target location] and then disregard" the robot, eventually resulting in collisions." However, with the touch interface, the same participant said that "if [the control] is on the screen, [she] is more likely to pay attention to where [the robots] are."

Collisions

By far, the primary user complaint overall was that the robots often collided in the multi-robot cases, with 15 users bringing it up in their written comments as making them change their approach and increasing the effort required. Collisions were not dramatic (i.e., there were no loud noises or damaged robots), but it often took the user special effort to separate the robots as they would push against each other. This really annoyed a few users, and several stated that they expected the robots to be smart enough to avoid each other. As five participants explicitly pointed out, users have to learn each robot's movement characteristics in order to make an efficient path plan and avoid collisions.

Two-Handed Interaction and Multitasking

One aspect we looked at is how users utilize their hands in the experiment and if they use both at the same time. Table 3 summarizes our findings, which are echoed in the user comments, showing how users found toy easier than touch in general for simultaneous hand use, and for the two-robot case the toys were used to work with both robots simultaneously rather than one at a time as they did with touch. In the three-robot case, however, users generally worked with one robot at a time for both the toy and touch interfaces.

Users reported that it was easier to operate robots simultaneously when the movement paths were similar and parallel rather than different and crossing, and more specifically they resorted to sequential movements when they felt that collisions were likely. Conversely, referring to the touch interface one user said: "whenever I use both the hands there are strong chances of [sic] robots getting collide with each other."

	question regarding robot use	toy	touch
2-robot	easy to control both simul.	78%	57%
	worked with both simul.	70%	43%
	worked with one at a time.	35%	74%
	used both hands simul.	61%	43%
3-robot	easy to control all three simul.	74%	48%
	worked with all three simul.	39%	26%
	worked with one at a time	61%	61%
	used both hands simul.	70%	52%

Table 3. Percentage of users that responded positively to questions about using both hands and controlling multiple robots simultaneously.

Complexity

We found a correlation between the number of robots and certain properties of the user responses. First, the conviction behind user response (how strongly they agree or disagree) decreased as the number of robots increased. Figure 7 shows the breakdown of how strongly users responded to four core questions asked throughout the experiment across the one, two, and three-robot cases, independent of the interface used, clearly outlining the trend to *weaken* their stance with the increasing number of robots. Further, the number of complaints (primarily regarding collisions) from the users in both the written questionnaires and during the experiment greatly increased as the number of robots increased. The trends of responses shown in Figure 6 suggests a general weakening of ease of use and control over the robot with the increased number of robots.

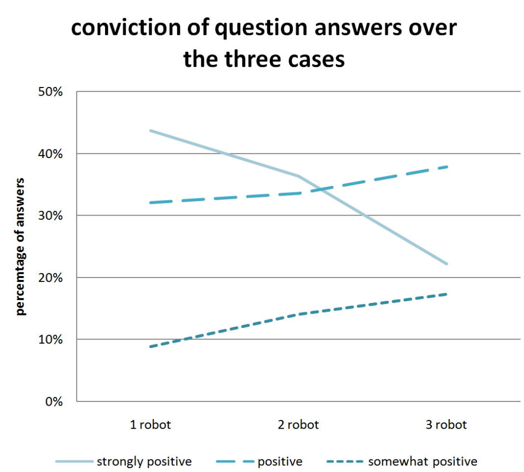


Figure 7. The *strength* of user answers across the robot cases.

Real Robots

In the post-test questionnaire users were asked if the experiment should have been done with a simulation instead of real robots. 15 of the 23 users felt that having real robots added value to the experiment. Reasons range from simple "the real thing is better" and "it is cool with real robots, more interesting than a simulation" to "real robots experience real problems. sims do not", "I trust the results more with real robots", "there was a real sense in knowing that real robots were colliding and that gave the situation more importance", and "real robots and the monitoring provided me with a better understanding of speeds and limitations that a simulation would have a hard time to capture."

DISCUSSION

Collisions and Cognitive Load

Collisions between robots was a large problem, slowing down the task, frustrating users, and increasing the concentration necessary to complete the task. Given the importance that users gave this problem and the descriptions they gave in the written feedback, we feel confident in directly linking increase in collisions to the drop in user rating of ease-of-use and the resorting to only using one robot at a time in the three-robot case.

The data clearly shows that increasing concern with collisions was due to users having more robots to worry about – more things to monitor at once puts higher demands on the user. It follows, then, that the collision-related complaints and problems are perhaps more accurately (and more simply) attributable to increased demand on the user, with collisions being another affect of this core problem. This agrees with Drury et al.'s HRI awareness taxonomy [5] and supports their claims regarding how human-robot ratios affects interaction. What we found particularly surprising is how discernible this effect was in our experiment, where only three robots are used with simple control mechanisms.

The number of robots is but one factor that influences user experience and usability. As the number of robots increases so does the demands on the user mental load, making it more difficult to compensate for interface limitations, which become more noticeable. This means that awareness and control problems will scale with the number of robots, and as such even seemingly minor interface flaws can become crippling.

The fact that a user reported paying more attention to a touch interface may suggest that although hiding low-level interface details from the users reduces their cognitive load, it can at the same time hinder their HRI awareness, and may lead them to forget certain important aspect of the task, possibly leading to undesirable incidents (such as collisions).

Toy and Touch

The very strong disparity between the results for the touch and toy interfaces, and the fact that it solidified with more robots, is a strong indicator that our toy interface was better suited to the task than our touch interface. Our data and findings frame a TUI vs touch set of results, but we must be careful with which conclusions we draw. User complaints with our touch implementation focused on the RNT technique, but had an overall effect on how *touch* was perceived. Applying our results to other touch interfaces needs to be done with care, and further experimentation will be necessary before drawing strong TUI vs touch-type conclusions.

Interface Design

User feedback directly outlined several problems with our interfaces. To improve intuitiveness, both interfaces should be improved to afford the robot limitations and movement properties and the fact that they move in a straight line (and do not replay user input). Alternatively, we need to consider other interface styles, such as enabling users to specify either a path or a target. Further, our interface could improve problems of visual clutter (e. g., when the robot did not line up perfectly with the input), impairing user ability to concentrate on their task. This has further implications for the toy interface, as the inaccuracy damages the input-output unification: while the robot is supposed to be where the toy is, the error reminds the user of the separation, a fact they have to consciously compensate for.

User Experience and Emotion

The users strongly favored the toy interface in most respects. Our results strongly link this success to core TUI concepts, as users explicitly and continually commented on the intuitive usability, the awareness gains, and the enjoyment they gained with the interface. This finding is quite significant and suggests that TUI interfaces should be explored in more depth for the remote control of robots. We believe that this relates to and supports ideas put forth through Dourish's tangible and embodied interaction [3], Norman's affordances [22], and core TUI literature [6, 7, 14, 31]. That is, the direct mapping between the toys and robots, and the tabletop, increases user comfort and lowers cognitive load by exploiting natural understanding of the physical world.

Despite this, toy and touch interfaces were generally equally *efficient* in terms of the task-completion time. We believe this points to a deeper, but perhaps simple, dimension to our results. The users simply found the toys *fun* and *felt* connected to the robots when using them, which had a direct effect on how users felt about the usability of the interface (helped them feel that they performed better, as in [21]). This is similar to how users defended the use of real robots due to the *cool* and novelty factor. These findings directly correspond to recent arguments for incorporating emotion into design, and HRI specifically (e. g., [21]).

Two Hands or One

The question of exactly when two-handed interaction is more effective is beyond the scope of our work, but in our experiments users resorted to one-handed interaction as things got complex, confusing, or difficult. This can be seen as another indicator of mental load, and a benefit of simpler interfaces – they may promote multi-hand interaction and the versatility that comes with it.

Implications

Here we distill our findings into a set of initial lessons and implications relevant for designing tabletop, touch, and TUIs for interaction with a remote group of robots.

- Users should not be expected to extrapolate the robot path, speed, and task just from the robot motions, but instead the interface should clearly indicate these properties to aid users in planning and interaction and to improve their HRI awareness.
- TUIs have a strong impact on user experience, regardless of particular efficiency gains, that can change how an interface is approached, perceived, used, and evaluated.
- Enabling users to specify complex, multi-part paths and commands relating to macro-scale robotic actions reduces user involvement and helps them cope with more robots in complex interaction scenarios.
- Users need to resort to lower-level control when the autonomy of the robot cannot solve a problem, such as a navigation complications or collisions. Good design should support this layer of detailed interaction as a backup option.
- Users may utilize both hands when interacting with a group of robots through tabletop, touch and TUIs. However, users may resort to single-hand interaction when they are faced with increasing cognitive load.
- Using actual robots (and letting the user know) changes the interaction experience in real ways that designers need to consider.

FUTURE WORK

We see a great deal of room for improvement in our interface design. We are exploring ways that would allow us to use more degrees of freedom on the TUIs to interact with the robot, and at the same time to express more of the physical state directly through the TUIs. With our studies being exploratory in nature, we believe our findings revealed only some of the basic lessons in using touch and TUIs for interaction with a robotic group, and we are planning to expand and improve on our experimentation.

We think it is important to explore an alternative (possibly improved) set of tokens and toys, ones that would contain more of the physical constraints of the robots. For example, we are planning to use toys with wheels that enforce the movement style and properties of the robots. As an extreme condition, we would like to test an interface based on a set of robotic TUIs that are identical to their coupled remote robotic team. Another, simpler approach we are considering is improvement in the visual feedback layer provided to the user (for both the touch and toy interfaces), such as a graphical template around the robot showing which directions it can move in.

Our current touch implementation brought to light interesting possibilities for improvement and we would like to explore how other touch techniques relate to our research problem, such as using touch gestures for moving the robot. Further, many of the physical properties of TUIs such as the three-dimensional nature or the natural collision detection can be ported to the touch interface, by restricting overlapping touch icons, or by using three-dimensional graphic visualizations rather than the current two-dimensional flat visualizations. We believe that improving our toy and touch interfaces will allow a more structured, and perhaps more conclusive, comparison between the two.

Our initial results suggest a correlation between one and two-handed use and the complexity of the task. We believe that this should be explored in more detail, both in terms of literature review and further experimentation focusing on the issue.

Mapping our touch and toy interaction approaches to more meaningful tasks will help us validate our approach. We are considering experimenting with our robots in more valid tasks in a lab setting. We are considering a group interface that will require the user to lead the robot through a simple spatial maze and will include collaborative tasks such as pulling and pushing objects. We believe using touch or TUIs only in combination with visual feedback is not versatile enough to tackle real world problems, such as urban search and rescue (USAR). Such applications should also consider combinations of interaction modalities such as speech and gesture input, as well as the more-traditional GUI and mouse.

CONCLUSION

In this paper, we have presented two novel interfaces and implementations for remotely interacting with multiple robots in real time using toys and touch. These interfaces support small groups of robots, using a tabletop computer as an interaction surface and provide detailed visual feedback on the robot location, state, and trajectory to enhance the user HRI task awareness. By conducting a qualitative empirical study of simple robot movement and group formation tasks, our analysis revealed several important relationships between the user experience and the properties of the interface used. We present our findings as a set of guidelines that researchers can use in their own interface design for remote robot control.

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