How to Walk a Robot: A Dog-Leash Human-Robot Interface

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***Abstract*— Human-robot interaction (HRI) tasks in everyday environments will require people to direct or lead a robot as they walk in close proximity to it. Tasks that exemplify this interaction include a robotic porter, carrying heavy suitcases, or a robot carrying groceries. As many users may not be robotics experts, we argue that such interaction schemes must be accessible, easy to use and understand. In this paper, we present a dog-leash interface that enables a person to lead a robot simply by holding the leash, following a dog-leash interaction metaphor. We introduce variants on dog-leash robotic interaction, present our original interface implementation, and detail our formal qualitative evaluation, exploring how users perceive and accept the dog leash robotic interaction.**

I. INTRODUCTION

WE present an interface which enables a person to lead a robot using a leash, similar to how they may lead a dog: an interface we call the *dog-leash robot* (Figure 1). We believe that this interface has potential to provide simple, yet practical and powerful, interaction with robots. For example, a nurse may bring along a medicine robot carrying supplies around a hospital, or an elderly person may take a robot shopping to carry their groceries.

Far from being a simple physical locomotion problem, the task of leading a robot (or an animal) on a leash consists of delicate interplay between the leader and the led that requires ongoing communication and interaction. This includes (for both entities) monitoring the other's movement direction and movement speed, feeling the direction of the other entity through the leash, pulling on the leash (subtly or deliberately), and adjusting actions accordingly in real time. Our dog-leash robot takes advantage of the fact that people already understand the idea of using a leash to lead something, from the established *social stock of knowledge* [1], and do not require training to employ these powerful communication characteristics. Through leveraging these existing abilities, our dog-leash interface makes the complex Human-Robot Interaction (HRI) task of leading a robot easy to understand and accessible to the casual user: interaction is as simple as holding the leash handle attached to the robot and leading it.

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Figure 1 – leading the dog-leash robot: robot in front (left) and robot behind (right)

Our implementation is based on a spring-loaded retractable leash design (popular with real dogs), where the person can hold the leash and walk naturally (Figure 1). We designed three implementation variants of the dog-leash interface: the robot in *front* of the person, the robot directly *behind* the person, and the robot *behind at an angle*. We conducted a formal user study, where we asked the primary research question: *can a person, without requiring training, use the leash interfaces to complete complex navigation tasks?* Our secondary research question was to compare the three leash interfaces and to build an understanding of how they differ. Our studies take a particular qualitative focus (as described in [2]) on the overall user experience of interaction: we considered questions of user comfort, emotion, and disposition toward the robot while using our interface, and aimed to *describe* interaction more than to measure quantitative data such as completion time [2]. We hope the results of this qualitative approach are useful for designing future, related, interfaces.

II. EXISTING ROBOT-LEADING INTERFACES

Tachi et al. [3] developed a guide-dog robot for the visually impaired which leads the person, rather than a person leading the robot. The robot requires detailed knowledge of the environment, tracks the person using active sonar, and the person wears a stereo headset which notifies them (via coded aural feedback) if they are straying from the path. No leash is used, there is no means to communicate to the robot, and the person must learn the new aural-feedback code: the robot serves as a beacon that communicates with the headset.

Ootake et al. [4] uses a leash to lead a robot. Force-sensors are used to detect the direction a person is pulling so that the robot can follow, meaning that a fixed-length string must be kept taut at all times. In addition to placing constraints on how the person must walk, this solution means that the robot must always be behind the person, and cannot follow at the side or be itself led from behind. This project is primarily a technical contribution and does not address the user-experience aspects of interaction. A similar project uses a retractable leash and a force sensor for leading a robot [5]. This implementation can only detect the force and direction – and not the length of the leash – and so the robot cannot make informed decisions to properly move with the person. As such, the user is expected to communicate with and control the robot using a gesture vocabulary consisting of light, medium, or strong pulls, the effect of which can change interaction modes and is dependent on the person's location in respect to the robot. In contrast, our interface does not require the user to learn gestures; the robot can simply follow without requiring explicit and intentional input from the user.

There is very little work that directly considers the social, user-experience aspects of a person leading a robot. One exception is a study on how a robot can follow a person naturally that compared two different methods: copying the exact path taken by the person, or taking a shortest path (cutting corners) – people reported the shortest path as feeling more natural, highlighting the fact that people do attribute notions of *natural* to following style [6]. Technically, this work used laser range-finder tracking techniques with no physical constraint or connection between the person and the robot. We believe that this problem is quite different from our case where a robot is being lead on a tethered leash.

The engineering problem of person-following robots has been approached by, for example, mounting laser range finders (e.g., [7, 8]) or cameras (e.g., [9]) on robots to allow them to detect and follow the person. These sometimes require pre-calculated maps of the environment, and can be prone to failures when occlusions occur or busy environments are encountered. Another approach is to mount an active device such as a sonar on the person for the robot to detect (e.g., [10, 3]), although this can be heavy and is still prone to occlusions, noise, and reflections; robust person-following remains an open problem.

Our approach of having a leash between the person and the robot improves the person-detecting problem as only one person will hold the leash at once, and the robot can know where that person is by monitoring the leash only. This improves technical scalability to crowded areas or rough and uneven terrain, improves control by giving the user a physical link to the robot, and the leash also provides a visible public cue to others of robot control and ownership. Our particular technical solution improves previous leash work as we detect both the angle and distance to the person while maintaining a retractable leash; this can smoothly change length to match a person's walking pattern (or stride), and enables the robot to be in any relative position (in front, behind, to the side) .

III. DESIGNING A DOG-LEASH ROBOT INTERFACE

Here we present our dog-leash interface for leading a robot, with three distinct variations: the robot in front of the person (shorthand as *front*), the robot following directly behind the person (*behind*), and the robot behind the person at an angle (*behind angle*). In all instances the research problem we attempt to solve is to create an interface that people can naturally understand, and quickly use with minimal (ideally zero) instruction.

Our leash interfaces are based on a spring-loaded retractable mechanism, where at rest the leash handle is at the robot, and can be pulled out to roughly 4 meters. This style of leash is common with dogs and so we expect it to be familiar to many people. There is a handle at the end of the leash (Figure 2), and while a person holds it there is slight tension from the spring: it is weak enough to allow the person to walk and move their arms naturally while the leash smoothly extends and retracts while they walk. The robot uses this leash only for all decision making – there is no global tracking or obstacle avoidance. Finally, we mounted a red emergency stop button on the handle at a location easily pressed by the thumb (Figure 2), as a means of alleviating safety concerns with the large and potentially dangerous robot.

Figure 2 – the leash handle with emergency button

A. Robot Following Directly Behind

This scenario is designed for the person to walk normally holding the leash, and the robot to follow behind at an appropriate distance (Figure 1 right). The person does not need to consider how the robot will move, turn, etc., but can assume that the robot will follow appropriately. If the robot becomes too distant, e.g., if the person moves too quickly for the robot to keep pace, the person will feel a tug as the leash runs out, forcing them to slow down or stop.

The robot is set to keep the leash roughly 1.7 m long (determined via pilot studies): as the length increases the robot moves faster to keep up, and if it decreases the robot slows down or backs away from the person. Simultaneously, the robot turns automatically to face in the correct direction toward the person, turning faster or slower based on the angle-distance. Thus, the robot automatically follows the person, as the person stops the robot automatically stops, and as the person changes direction the robot automatically adjusts trajectory – no robot actions need to be specified by the person.

B. Robot Following Behind at an Angle

This is the same as the *behind* case except the robot aims to stay at an angle of 45° behind the person (Figure 3). This was a direct attempt to improve visibility of the robot (*behind angle* is easier to see in periphery

Figure 3 – robot following behind at an angle

vision than *behind*), although more space is required to lead the robot as it stands further off to the side. The side the robot follows on is dynamic depending on what is easiest to reach: e.g., if the person changes the direction and the leash crosses the robot's axis before it can catch up, it will change following side to catch up quicker. We leave the questions of interaction dynamics related to following side as future work.

C. *Robot In Front of the Person*

Placing the robot in front of the person enables it to be easily monitored during operation. As our robot was not quick enough to stay in front of a walking person automatically, we implemented a simple push-stick metaphor (Figure 1, left side). The person leads the robot from behind as if it was attached to a rigid stick; the spring-loaded leash makes interaction less rigid than with a stick. As the person walks toward the robot and the leash gets shorter the robot moves away from the person, such that the person can walk at a comfortable pace and the robot stays in front of them. As the person slows down or stops, the robot does likewise to maintain leash length. If the person backs away and the leash gets longer, the robot also backs up to correct the leash length.

Much as how a wheeled object on a stick tends to stay straight when pushed, the robot tries to keep the leash aligned with its front-back axis during movement, while simultaneously adjusting speed to keep at the appropriate distance: as a person walks they do not have to manage small deviations in their path. For large turns, the person walks to the side of the robot as if to gain a better point from which to push the robot: to turn the robot left, they walk to the robot's right side and toward the robot as if they were pushing it with a stick. In this scenario the robot keeps the leash at a length of roughly 1 m (determined via pilot studies, explained below).

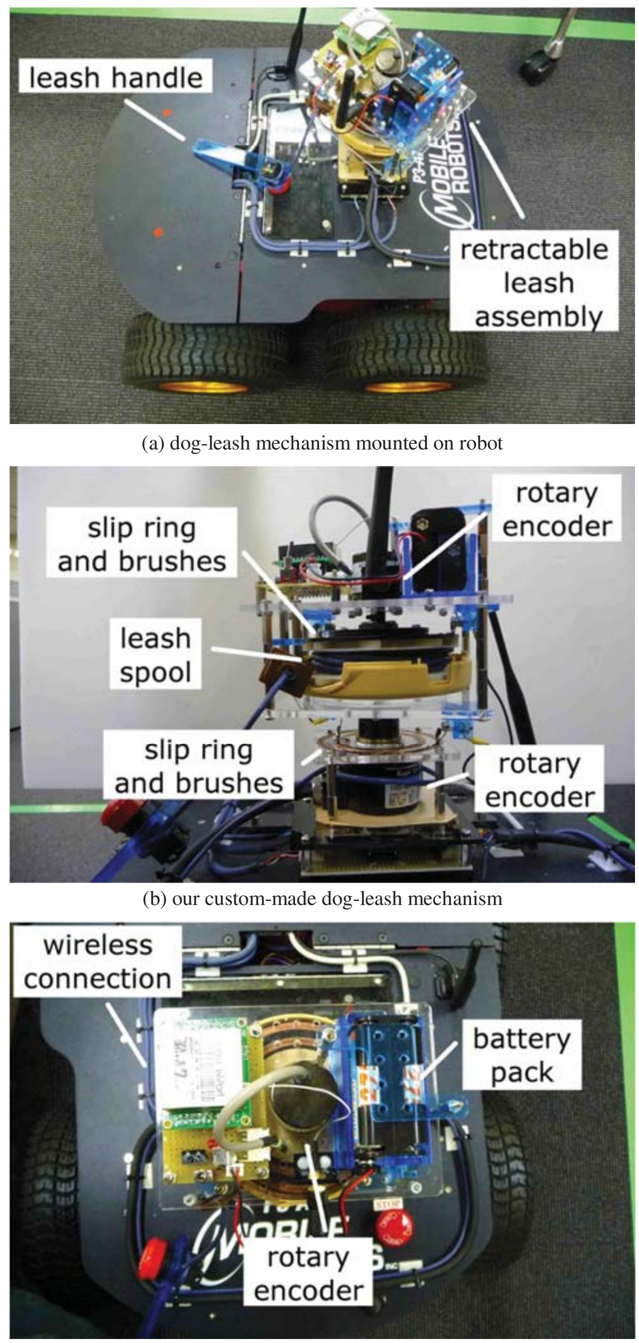
IV. Implementing the Dog-Leash Interface

We used the Mobile Robots Inc. 3-AT 4-wheel robot and used a standard PC for control; all software used C++ or Java. We built the dog-leash mechanism (Figure 4) using an off-the-shelf retractable dog leash, mounted atop the robot on an absolute (720 ticks / rev.) rotary encoder (Koyo Electric TRD-NA720NW). The assembly can rotate freely: as a person pulls the leash and walks around the robot, the rotary encoder senses the leash direction, and thus the person's direction (Figure 4b). This information is sent to the controlling PC using a Lantronix 802.11g WiPort modem.

The leash string is stored on a spring-loaded spool which can be pulled out and will automatically retract if released (Figure 4b). We use a relative (spin-directional) rotary encoder (COPAL Electric 100-213-1, 64 ticks / rev.) to sense when the string is being pulled and released, and to estimate the current length of the pulled string (number of revolutions). This information is sent to the control PC using an additional 802.11g WiPort modem (Figure 4d). Thus, the controlling PC senses both the angle and the distance (leash length) to the person, and can estimate the person's relative location in polar coordinates. Following, the PC generates appropriate robot locomotion commands to follow the person.

We were unable to run cables from the leash mechanism to the robot as the whole leash spool (mounted on the rotary encoder) must spin freely in 360° to facilitate natural walking. As such, we completely contained the top encoder, modem, and batteries on top of the leash assembly (Figure 4c).

We implemented the on-leash emergency stop button by replacing the leash string with two-strand wire, connecting the (normally-closed) button to the existing emergency-stop mechanism. When the button is pressed, the circuit is opened and the robot stops moving. We connected this wire from the leash to the base robot through two sets of slip-ring-and-brush assemblies – once from the spinning spool to the main assembly, and once from the assembly to the robot (Figure 4b). Also, the robot would stop if the leash assembly breaks as the emergency circuit would go open.



(a) dog-leash mechanism mounted on robot

(b) our custom-made dog-leash mechanism

(c) a top-view, showing the leash-length sensor assembly

Figure 4 – dog-leash robot implementation

For control we use a closed feedback loop, where the robot constantly monitors the person's position and fine-tunes its own behavior in real time (15 Hz). For each leading style (*behind*, *behind angle*, *front*) we defined rough target leash lengths and relative position to the person. We have further defined movement instructions for reaching targets based on current state, e.g., the robot may have to turn around before moving forward. Whenever possible the robot combines forward/backward movements with turning for smooth operation, and we further scale movements based on distance to target, smoothing the overall movement.

V. EVALUATING THE ROBOTIC DOG-LEASH INTERFACE

The primary evaluation purpose was to test interface usability, whether people could easily lead the robot. We also explored participants' emotional states, such as how they feel about the dog-leash robot when it is in front of them, behind them or to the side, as a means of deeply exploring the overall interaction experience. Finally, we performed an initial test relating following distance to comfort.

A. Design Critiques

We first performed several preliminary in-lab, informal design critiques to help fine-tune the interface and behaviors. We originally implemented leash gestures where the robot could detect a single or double "tug," and react accordingly, for example, to pause or move more quickly. However, initial testing found these gestures to be confusing, and we omitted them from the study.

Trials with the *behind* case found that people chronically turned to look behind them at the robot, citing safety concerns over the robot colliding with objects in the environment: this led to the development of the *behind angle* interface. We further found that the robot was frightening when following too closely behind, and decided through testing to have the robot follow at 1.7m behind. On the other hand, having the *front* robot too far away hindered turning ability, and having it closer (1 m in this case) improved control.

B. Tasks

The primary task was to follow a route with the robot and to pick up and deliver objects (robot-carried) to designated locations. The path (Figure 5) had long and short passages, wide and narrow curves, and obstacles (plastic cones).

An additional task measured participants' comfort distance when approaching and withdrawing from the robot, holding and not holding the leash. The participant moved at whatever speed they like and stop as soon as they felt (or no longer felt) comfortable with the distance.

C. Study Procedure

We used a structured protocol, informed consent forms and questionnaires. The pre-test questionnaire targeted prior experience with robots and related technology such as driving cars or operating machinery, and with pets (particularly dogs). Participants were then introduced to the robot and shown how to use the emergency-stop button.

The participants completed the same tasks for each of *front*, *behind*, and *behind angle*. Participants tested each behavior,

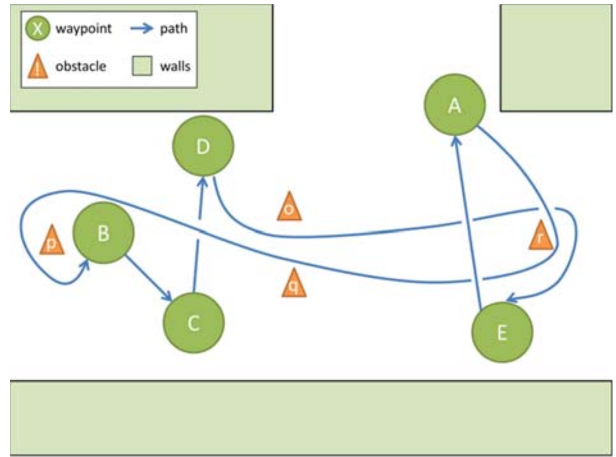


Figure 5 – the path and way points, participant starts at E to go to first point A

then completed two pickup/delivery circuits (Figure 5). Questionnaires were administered after each behavior to explore participant reactions. We used the SAM scale [11] to enquire about emotional state on *pleasure* and *arousal* nine-point Likert-like scales; we also administered SAM pre-test to serve as a comparison baseline. We used variants on the GODSPEED questionnaires [12] to measure perceived safety and likability.

After conducting the comfort-distance task (post-test), we asked various free-form questions relating to participants' impression of the robot, feeling of safety, if they felt in control, and their overall preferences. Also, we used NARS [13] during both the pre- and post-test phases to explore participants' disposition toward robots and how it changed through participation. NARS assesses a person's general opinions of robots on three scales: negative attitudes toward situations and interactions with robots (*interaction*), negative attitudes toward social influence of robots (*social*), and negative attitudes toward emotions in interactions with robots (*emotion*). Lower scores are more-positive responses.

D. Study Design

The main independent variable in this study was the robot behavior type: *front*, *behind*, or *behind angle*. We used a within-subjects design, such that each participant did the tasks with each behavior, order counterbalanced between participants. The study took place in Yokohama, Japan, in a model-home complex called HouseSquare Yokohama. Twelve male right-handed Japanese students ranging in age from 20 to 23 (M=21.1) participated in the study, for which they received ￥4500 (Japanese Yen, approximately $53 2010 US Dollars) for their participation.

E. Results

All participants completed all tasks without problem, major incident, or requiring assistance from the experimenters. Figure 6 outlines the general overall response to the system elicited through questionnaires. We present participant rankings (on three categories) of the behavior types in Figure 7. While Friedman's ANOVA failed to expose significant effect of behavior type on preference, an effect was found for the participant feeling the most in control ($X^2(2)=6.62$, $p=.037$,

	1	2	3	4	5	6	7	
not controllable	1	2	8	7	10	6	2	controllable
not predictable	1	1	7	6	8	9	4	predictable
not autonomous	0	3	10	6	11	5	1	autonomous

Figure 6 – cumulative result table of perceived-control questions, value represents # of participants who gave that response

ranking	I liked ... best			I felt most in control with...			I felt the robot did what I wanted it to do the most for...		
	behind	beh. angle	front	behind	beh. angle	front	behind	beh. angle	front
3	1	8	4	3	8	2	2	8	3
2	9	2	2	6	4	3	6	4	3
1	3	3	7	4	1	8	5	1	7

Figure 7 – result table of how participants ranked the behaviors in relation to each other. Each number represents how many participants ranked that given behavior as first, second, or third, for each question.

we do not report effect sizes for Friedman's ANOVA due to the problem of clear calculation [14]), and the analysis suggests a trend toward behavior impacting the robot being rated as doing what the participant wanted it to do ($X^2(2)=5.69$, $p=.058$). Six participants stated (via post-test questionnaire) that they would recommend a friend *front*, three would recommend *behind*, and three would recommend *behind angle*.

As we measured emotional state (via the SAM scale, on the *pleasure* and *arousal* axes) pre-test and post-behavior, we calculated the change in emotional state after each behavior type in comparison with pre-test (Figure 8); only eleven responses are included as one participant did not complete the questionnaires. The table shows how pleasure increased in comparison to pretest for the *front* condition, and decreased for the *behind angle* condition. Friedman's ANOVA failed to reveal an effect of behavior type on change in pleasure, but found an effect on arousal ($X^2(3)=23.67$, $p<0.001$). Post-hoc Wilcoxon Signed Ranks tests, with a Bonferroni correction (six cases, significance at $p=.008$) failed to reveal further relationships ($p>.2$). No effect was found of behavior type on reported enjoyment of interaction after using each behavior.

Many participants stated that they felt in control of the robot (*behind*: 8, *behind angle*: 4, *front*: 8). On the other hand, many participants commented that the robot was unpredictable and it did not move as they wanted or expected (*behind*: 7, *behind angle*: 10, *front*: 5), with comments

change in pleasure	behind	behind angle	front
4	0	0	0
3	1	1	1
2	1	2	2
1	3	0	5
0	3	3	0
−1	0	0	1
−2	2	4	2
−3	1	0	0
−4	0	1	0

(a) change in *pleasure* in comparison to pre-test, positive indicates change toward positive end of scale

change in arousal	behind	behind angle	front
4	0	0	0
3	1	0	2
2	0	4	4
1	4	2	0
0	3	3	2
−1	2	0	1
−2	0	1	2
−3	1	0	0
−4	0	0	0

(b) change in *arousal* in comparison to pre-test, positive indicates change toward excited / anxious end of scale

Figure 8 – tables of number of participants who had particular changes in emotional state as measured by the SAM scale [11]

specifying difficulty controlling speed and turning. Note the disparity between responses to *behind angle* and the other two. Responses to per-behavior questions on perceived control (relating to controllable, predictable, autonomous) were positive 51%, neutral 18%, and negative 31%, and Figure 9 shows responses to general questions of impressions of the robot. Friedman's ANOVA tests did not reveal any effect of behavior type on any question.

When asked about robot visibility, it was only mentioned as a problem for the *behind angle* behavior, and was surprisingly not mentioned for walking directly *behind* (*behind*: 0, *behind angle*: 5, *front*: 0).

Figure 10 shows how the results of the GODSPEED V perceived-safety questionnaire [12] generally indicated a safe or neutral disposition. We found a significant effect of behavior on how participants rated their feeling on the *surprised* to *quiescent* scale (Friedman's ANOVA, $X^2(2)=9.53$, $p=.009$), although post-hoc Wilcoxon Signed Ranks Tests (with Bonferroni correction for significance at $p=.017$, three cases tested) failed to reveal further significant relationships. On the *agitated* versus *calm* scale participants tended to be more agitated with the robot *behind angle* ($X^2=5.25$, $p=.072$, average ranks: *behind*=2.33, *behind angle*=1.58, *front*=2.08). No effect was found for behavior type on the other scales.

The comparison of general disposition toward robots before and after our study is shown in Figure 11 as the average results of each of the three NARS scales; these results are on a scale from 1 (not negative) to 7 (negative). Note that

	1	2	3	4	5	6	7	
dislike	0	0	7	5	11	10	3	like
unfriendly	0	4	6	6	10	8	2	friendly
unkind	0	3	12	9	9	2	1	kind
unpleasant	0	3	5	9	10	8	1	pleasant
aweful	0	1	4	5	17	8	1	nice
aggressive	2	3	6	7	12	6	0	non-aggressive

Figure 9 – cumulative result table of the questions targeting participants' impressions of the robot, value represents number of people who gave that response

GODSPEED V: Perceived Safety	1	2	3	4	5	6	7	
anxious	0	3	9	5	13	6	0	relaxed
agitated	1	5	5	12	11	1	1	calm
quiescent	0	1	5	7	12	9	2	surprised
unpleasant	0	3	5	12	10	5	1	comfortable

Figure 10 – cumulative result table of the GODSPEED V questionnaire on perceived safety, lower scores are unsafe [12]; value represents number who gave that response

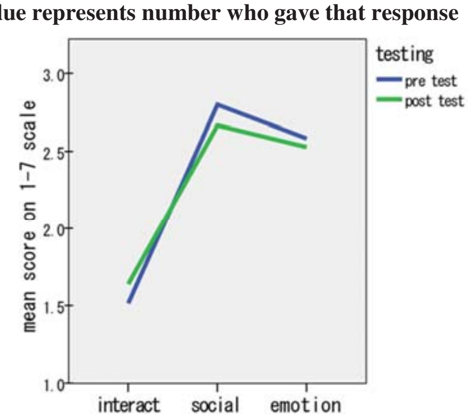


Figure 11 – the result of the NARS questionnaire

responses were generally low, meaning disposition toward robots was fairly positive, particularly on the interaction scale. A two-way repeated-measures ANOVA (test: pre or post-test by scale type: interaction, social, or emotion) found a main effect of scale type ($F(2,22)=44.33$, $p<.001$), with general pattern matching the same relationships found by [12]. Contrasts revealed that ratings of scale *interact* were significantly lower than both *social*, $F(1, 11) = 75.61$, $r = 0.93$ and *emotion*, $F(1, 11) = 71.12$, $r = 0.93$. No significant effect of test time or interaction was found, meaning that the measurement did not detect any change in disposition toward after the test in comparison to before.

Participants used the emergency stop button for its planned purpose, i.e., for preventing accidents and in case of emergency. Observation and preliminary data analysis suggested no effect of behavior condition on emergency button use. Participants also used the emergency stop button as a means to temporarily pause the robot, even though they could simply stop walking for the same effect: the robot would automatically stop. Several participants commented that the robot was hard to stop (*behind*: 2, *behind angle*: 5, *front*: 6); the emergency-stop button resulted in a complete system shutdown and, once released, the robot took roughly 10 s to automatically resume.

Figure 12 details the results of the preliminary comfort-distance measuring study phase, for the approach and withdraw conditions. We present the differences between leash and no leash per participant to focus on the difference between the conditions. While the figure suggests that holding a leash requires a further distance from the robot for comfort, a two-way repeated-measures ANOVA failed to find a significant effect of with / without leash or withdrawal versus approach on comfort distance, and there was no factor interaction observed. Further, note how in all but one case the relationship between holding the leash and the comfort distance did not depend on withdrawal or approach: if a person preferred the robot further away while holding the leash, this was the same for both withdrawal and approach.

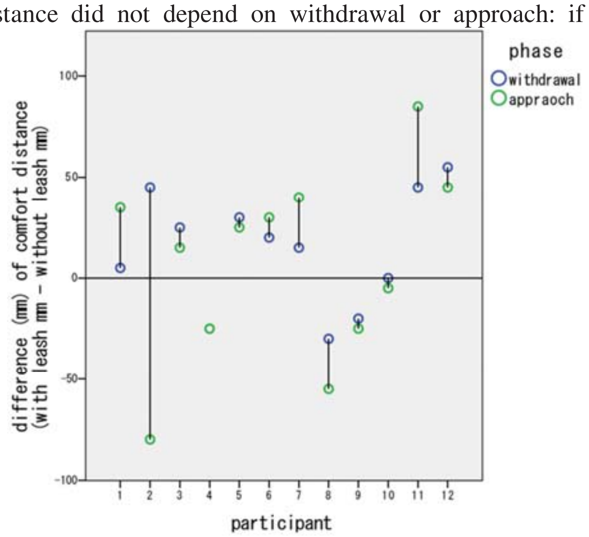


Figure 12 – comfort-distance difference when the participant is holding the leash versus no leash. The more positive the value (>0), comfort distance is further while holding the leash. The more negative a value (<0), comfort distance is closer with the leash. The vertical lines indicate the disparity of the comfort-distance relationship between the withdraw and approach cases.

F. Discussion

That all participants completed their tasks – with only a brief demonstration and without trouble requiring assistance – suggests that the leash interface was successful in its goal of enabling the general public to easily direct and navigate a robot. Further, the participants themselves were much more positive than negative (Figure 6) regarding the robot being relatively easy to use (controllable and predictable), generally liked the robot, and were fairly relaxed while operating it (Figure 9, Figure 10). The GODSPEED V questionnaire [12] results suggest that people generally felt safe toward the robot, and at least did not feel unsafe, and NARS indicated general positive attitudes toward the robot. Overall, this supports the idea that the general public is both capable and comfortable with using our dog-leash interface for robot control, answering our primary research question.

That our study did not show any impact on disposition toward robots was a surprise, as we expected the ease-of-use experience to be encouraging for participants. However, perhaps it is simply that robot expectations are already much higher than achievable given modern technology [15].

Our data further uncovers detailed differences between the following styles. The *front* behavior was generally preferred, with seven people (58%) explicitly ranking it as their first choice, and half saying they would recommend it as the best to a friend. There was a tendency toward this preference throughout the rest of the study data, although statistical tests failed to find strong numerical results. Given the relatively low power of our non-parametric tests used and our sample size of twelve participants, and the tendency found in our data, we believe there is a reasonable chance of a type 2 error and that this is a relationship worth further exploration.

General negative response to the *behind angle* was a prevailing theme throughout the study, particularly in terms of cited usability and control problems. Participants reported that the *behind angle* was harder to see, gave a worse sense of control and tended to make them feel less safe and more agitated with the robot. Particularly surprising is how this feedback compares to the *behind* case: the same complaints were not mirrored in the *behind* case even though some of the same *behind-angle* problems could be reasonably expected (e.g., that the robot is not directly in sight of the person). This contradicts the original design intent of *behind angle*, that is, improving visibility over the *behind* condition and thus requiring less effort. One hypothesis is that perhaps the *behind angle* had a wider footprint, i.e., the robot was to the side of the person and so as a team they required more width-space to move, resulted in increased difficulty of control and added a negative overall feeling.

This study points to the need of an explicit robot pause mechanism, given that the robot's emergency button was primarily used for merely pausing movement. While the robot does stop when the person stops, people reported that they felt uneasy about this and wanted a more explicit mechanism. Perhaps this is related to trust in the robot, where an explicit mechanism could afford more explicit, direct control.

Results from our comfort-distance task failed to reveal any conclusive effect of holding a leash, or approach versus withdrawal, on people's preference for robot distance. One caveat with our comfort-distance study is that it was conducted with the person approaching the robot, whereas in real-life scenarios the robot would likely be approaching the person. Further we did not control for movement speed. We believe these factors may impact the results as, for example, the person approaching the robot is in control, while they may feel a lack of control if the robot is approaching them.

VI. Future Work

The dog leash interface is a versatile platform and there remain various future-work questions which we hope to explore using it.

There is only a limited scope on the kinds of answers we can derive from our particular study and further studies would be needed to explore such questions as at what distance should the robot follow (during movement) and how does this distance relate to following position, or how does culture or gender relate to dog-leash interaction.

One question of particular interest is the leash versus no leash variable, for example, how does being tethered to the robot relate to a person's feeling of responsibility, affect comfortable following distance, interaction style, or how people perceive the robot? What would have changed if instead of using the physical leash, following was based on other, non-physical sensors of distance and direction? We hypothesize, for example, that people may be more comfortable with a physical connection to the robot. Another question is how does interaction change when other people are nearby, for example, does the operator get performance anxiety? Are they more sensitive to robot mistakes due to others being in the vicinity, very much like a person would often feel responsible for a misbehaving dog?

We are further interested in how other people feel about someone leading a robot around, particularly in public spaces where other people (and their children, or perhaps pets) could be injured by such a robot. While we expect that people not leading the robot, such as bystanders or a passerby in a crowd, likely understand from *the social stock of knowledge* [1] what is happening when they see a person leading a robot, future evaluation would be needed to test this hypothesis.

For the design we relied on our common-sense understanding of using a leash from *the social stock of knowledge*. Another direction for future work is to look to the formal literature on human-dog interaction and training to better inform our interface and interaction designs.

Finally, the implementation itself can be improved to help the robot make better decisions and do a better job of keeping up with the person. One future work question in relation to this is how to integrate the current system with robust object avoidance – currently, the robot has no sense of its environment except what it gleans through the leash.

VII. Conclusions

In this paper we presented the idea of leading a robot on a leash as one may a lead a dog. We discussed existing related approaches and detailed three interface styles that we designed, implemented, and formally evaluated.

The results of our dog-leash interface work demonstrate that the dog-leash interaction metaphor leverages peoples existing skills to make a difficult robot interaction problem accessible: the general public was able to complete complex robot-direction tasks using the dog-leash interface with very minimal to no training. In addition, we have learned a great deal regarding the different robot following styles, *behind, behind-angle*, and *front*, that can be useful for directing future efforts. While we argue for the simplicity of this interface, the greater *holistic interaction context* [16] within which a person leads a robot makes this interaction anything but simple. As outlined in the future work above, there are many important remaining questions regarding how such a dog-leash interface would be used and integrated into actual real-world scenarios.

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