Haptic Interaction for Human-Robot Communication Using a Spherical Robot

Xiang Zhi Tan[1] and Aaron Steinfeld[2]

***Abstract*— We demonstrate a system of adding an additional human-robot communication channel using a spherical robot through kinesthetic haptic signals. While not designed for this type of interaction, we show that the robot could be used to generate kinesthetic haptic signals through asymmetric rotations. These rotations generate pseudo-rotations that are detectable in a user's palm and can convey both rotational and directional information with proper training. We present two user studies that explore potential types of distinguishable haptic signals. While some participants were able to rapidly identify the different signals, other participants expressed the need for more training. We also describe use cases we believe would benefit from such interaction and general guidelines for spherical haptic devices.**

I. Introduction

Human-robot communication has generally relied on the commonly used visual or audible channels. Although these channels carry dense information, they are susceptible to environmental factors or unsuitable for user groups who are unable to utilize these channels. People who are blind or low vision encounter challenges when using existing vision-based communication (screens, buttons, etc.) and auditory communication is highly affected by environmental noise. These issues are exacerbated for people who are both deaf and blind. To address this, we demonstrate how existing commodity robotic platforms could extend communication through haptic interactions. While similar haptic devices exist and are useful in a wide range of services [1], [2]. Our work focuses on how to extend this capability to a low-cost spherical device not designed with these interactions in mind.

Human-robot communication is the bi-directional flow of information from the human to the robot (input) and from the robot to the user (output). For spherical robots, users can move the robot to issue commands and convey intent. Prior work has shown how these robots can be used for such interaction [3]. Our work looks at the second part of the interaction – how spherical robots can communicate complex information to the user beyond the use of simple vibration. For this work, we investigated how to generate kinesthetic (proprioception) signals on a widely available commercial spherical robot toy. The low cost and durability of the toy makes this platform an interesting option for applications that lack a large enough user base to support specialty equipment.

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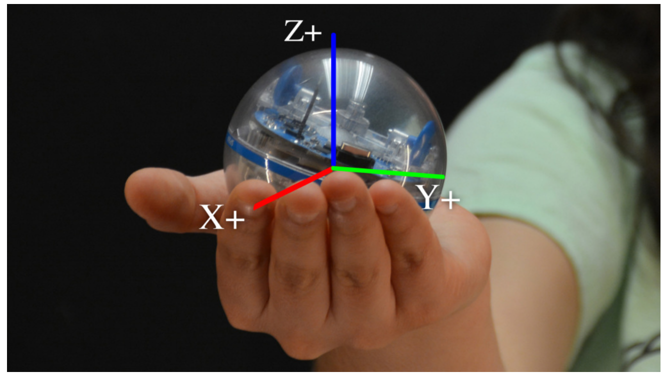


Fig. 1: Our explored commodity robot, a Sphero SPRK+, in the hand of an adult for scale and our reference coordinate frame.

The spherical shape is also appealing in that it supports a wide range of grasps and postures.

One way to generate kinesthetic signals in a spherical, compact form is through rotation of a hemisphere-shaped weighted carriage inside the shell. We developed candidate rotations and evaluated the effectiveness and usefulness of the resulting haptic interactions through two user studies. Based on what was learned during this exploration, we also examined possible use cases and design implications for spherical haptic devices.

II. Related Work

In this section, we review how kinesthetic haptic devices have been used in prior research within the context of human-computer interaction (HCI) and robotic applications.

A. Kinesthetic Haptic Devices in HCI

We can categorize kinesthetic haptic devices into two groups, depending on whether or not they are grounded (attached to a surface). Grounded kinesthetic haptic interfaces, such as the Phantom [4], have shown to be useful interfaces for applications that include interacting with virtual worlds [5] and rehabilitation [6]. However, grounded devices are unsuitable for applications that require mobility. Compared to grounded kinesthetic haptic devices, ungrounded devices have been less explored because they must generate forces while being held, which is a difficult engineering problem. One of the first examples of ungrounded kinesthetic haptic devices was the TorqueBar [7]. This device generated forces through shifting a mass on a metal rail. Another method commonly used to generate kinesthetic haptic forces is a gyroscope effect from one or more flywheels [8], [9]. Winfree and colleagues [9] developed a handheld kinesthetic haptic device called iTorqU 2.0 that controlled the generated torque from a single, rotating flywheel. Our work shares similarities with work done by Amemiya and Sugiyama [1], who created a custom handheld haptic device that used the same principles that we use in this paper. They called the perceived sensation ”pseudo-attraction force” and were able to generate forces in 8 cardinal directions. Amemiya and Gomi [10] expanded work on pseudo-attraction force into the rotational space by creating a device that could generate torque through sudden asymmetric accelerating rotations around a single flywheel. Our approach expands upon this work by using commodity hardware and not being limited to one axis of rotation.

B. Haptic Interaction for Human-Robot Interaction

In human-robot interaction (HRI), research on the haptic channel has often focused on tactile haptic interaction [11]. These interactions focus on recognizing affective touch by users or drawing symbols on the robot to communicate information. Yohanan and colleagues [12] explored the different types of affective touch for small, creature-like robots and found five distinct types that convey different emotional meanings. Arnold and Scheutz [13] found people view a robot that initiates touch during a human-robot collaboration task as more capable and intelligent. However, research on using haptic interaction as an explicit method of conveying information in HRI has been sparse and has primarily been used in teleoperation to convey additional information from the controlled robot [14].

III. Generating Haptic Signals

Our approach relies on the simple mechanisms of direct torque and asymmetric acceleration, similar to the approach described in prior work [10]. However, we expanded the capabilities from just rotating around one axis of rotation to use potentially any axis in 3D space. The device creates motion by driving a hemisphere-shaped weighted carriage inside a sealed sphere, thereby spinning the exterior surface like a wheel. As we command a sudden change in the angular acceleration of the carriage around a rotation axis, a user holding the exterior of the device experiences a small torque in the opposite direction. This torque comes from the torque of the internal carriage pushing off of the internal surfaces. The torque generated by the device depends on the change in angular velocity of the carriage. Torque is defined as the moment of inertia (I) times the angular acceleration.

$$\tau = I\alpha \tag{1}$$

where α is the angular acceleration and could be rewritten as change in angular velocity over time.

$$\tau = I\frac{d\omega}{dt} \tag{2}$$

The larger the sudden change in the angular velocity of the system, the stronger the torque. To control the direction felt by the user, we used the principle of asymmetric acceleration, which has been explored in prior work [1], [10]. The direction is presented by first generating a large acceleration in the desired direction followed by a smaller deceleration and slow rotation in the opposite direction. This generates the strong feeling of being pulled towards the desired direction without feeling much of the pull backwards as the device decelerates. In contrast with prior work, our method generates a pseudo-rotation that results in a torque sensation instead of a force sensation. An illustration of a single rotation together with measured torque is shown in Figure 2. Furthermore, we can rotate the center of mass to reorient the axis of rotation in 3D space and create a sense of pulling along any direction. In summary, the user can theoretically feel the device pulling clockwise or counterclockwise around any axis of rotation. As we control the speed, timing, and axis of rotation, we are able to provide a rich design space to create meaningful interactions.

IV. Spherical Robot System

The spherical robot used is a widely available commercial spherical robot, SPRK+, manufactured for educational purposes[1]. Each unit has a diameter of 3 inches (7.62cm) and weighs about 1 lb (0.453kg). It is designed and sold as an educational toy that can be programmed to drive around indoor spaces. The low price, durability, and programmability of the robot has been leveraged in other research settings, such as teaching programming [15], studying children with Autism Spectrum Disorder [16], and use as a GUI [3].

The robot includes an Application Program Interface (API)[2] that we utilized for this work. A Linux laptop controlled all motion through Bluetooth 4.0 Low Energy Protocol (BLE). While the configuration used here required a laptop, the same code could be easily ported to a BLE-supported smartphone. The software we developed to explore haptic interactions is open-sourced and available online[3].

V. Design Space

In this section, we explore the basic characteristics of pseudo-rotation and the subsequent design space created from these criteria. While some of the generated pseudo-rotations might be intuitive to users, different rotations could be mixed and matched to encode semantic signals, similar those described in prior work [17].

A. Torque

The torque felt by the user is directly controlled by the change in the angular velocity. As we command the device to move from one rotation direction to another, the generated torque on the shell creates a lingering feeling of being pulled in that direction. The larger the change in angular velocity, the stronger the torque felt by the user. The range of angular velocity in a flat configuration ranges from -1.75m/s to 1.75m/s.

[1] http://www.sphero.com/sprk-plus
[2] https://sdk.sphero.com/
[3] https://github.com/CMU-ARM/Spherical-Robot-Haptic

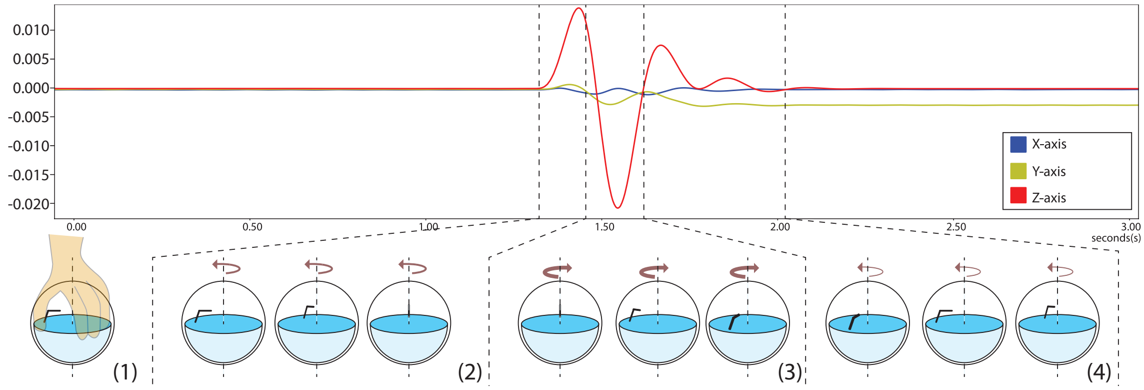


Fig. 2: Illustration of the different phases of a single clockwise rotational signal together with the measured torque by an ATI Mini40 Force Torque Sensor. The arrows above the device show the directions in which the shell moves. From left to right: (1) The device is stationary to begin. (2) The internal carriage spins towards the desired direction and the torques pushing the carriage push the shell slightly in the opposite direction. (3) A sudden change in angular acceleration is generated as the carriage rotates in the opposite direction, generating a large torque pushing towards the desired direction that is detectable by the user's hand. (4) The device slowly decelerates back to the neutral position, avoiding any sudden spikes in acceleration.

B. Axis

The most unique component of our approach is the ability to change the axis of rotation by commanding different values to each of the two internal carriage motors. As the system does not have a fixed coordinate frame, we define a coordinate frame relative to the user. In this coordinate frame, the positive X-axis points forward towards where the user is looking, the positive Y-axis points leftwards away from the user and the positive Z-axis is perpendicular to the ground and points upwards. An illustration of the coordinate frame is shown in Figure 1. Our device can spin around the Z axis by driving the motors in alternate directions. However, when both motors are moving in the same direction, the axis of rotation shifts and is relative to where the carriage started rotating upwards/downwards.

Beyond aligning itself to the principal axes, an imbalanced motor control (e.g., commanding one motor to move faster than the other) will shift the axis to be skewed in one direction. We are unaware of any rotational axes that are theoretically unachievable by our approach. A sample of possible rotational axes are demonstrated in Figure 3. However, we are unable to consistently maintain all possible axes of rotation in the SPRK+ due to system constraints. Maintaining axes that are not parallel or perpendicular to gravity is challenging due to the different gravitational forces being exerted on the motors and the internal system not being fast enough to actively compensate the pull of gravity.

C. Spin direction

The rotation can be configured to be either rotating clockwise or counter-clockwise around the set axis.

D. Timing

The timing of the torque pulses (sudden changes in acceleration) can be easily altered by the application, from one single pulse to a maximum of 10 pulses per second. The maximum number of pulses is due to the system's communication bandwidth. However, our preliminary tests show that users are probably unable to distinguish more than five pulses per second. The timing can also be changed between pulses to give a sense of speeding up or down.

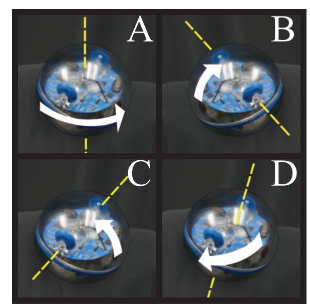


Fig. 3: Illustration of torques generated with different axes of rotation. (A) Axis of rotation is perpendicular to the ground. (B, C) Axis of rotation is parallel to the ground. (D) Axis of rotation is skewed to one side.

VI. Haptic Perception Study

To understand the ability of people to recognize these signals, we conducted two user studies. The first user study focused on people's ability to distinguish different torques and haptic signals with different characteristics. The second user study improved on the first study and focused on the signals' intuitiveness and recognition.

A. User Studies Procedure

For both user studies, participants were asked to complete two tasks where they responded to specific haptic singals. During the study, participants were given headphones to block the low frequency noises generated by the robot. Participants were also asked to hold onto the robot and place their hand in a cardboard enclosure. Both preventive measures were included to remove possible influence by audio and visual cues. Between tasks, participants were given distraction tasks (drawing or completing a survey) to provide them with a break. At the end of both studies, participants also completed a questionnaire on their general impressions and demographic information.

VII. User Study 1 - Haptic Perception

A. Tasks and Participants

In task 1, participants were asked to rate the perceived exerted torque of the device on a scale of 1 to 7, with 7 being strongest and 1 being none. Participants were given a benchmark by first experiencing the strongest setting followed by five different levels of torque in a random order and asked to rate each on a scale.

Task 2 consisted of two rounds of classification. Each round included four haptic signals. Participants were first instructed on each signal three times in a row, followed by a single replay of all signals. They were then asked to classify five trials of each signal, for a total of 20 trials, in a random order. The first round consisted of directional signals: *Left*, *Right*, *Forward* and *Backward*. Both *Left* and *Right* were signals that pulsed either clockwise (right) or counterclockwise (left) around the Z-axis twice. *Forward* and *Backward* signals were generated by pulsing clockwise (forward) and counterclockwise (backwards) around the X-axis twice.

The second round of signals were symbolic signals that had no direct mapping to any interactions in real life. We envision such signals as representations of non-directional information and they are designed to be distinct from the directional signals. Unlike the directional signals, they were designed to be learned and attached with associated meanings by the application designer (e.g., "stop" or "acknowledgement"). We tested the following signals:

SR Shifts sideways and downward in the clockwise direction twice.

SL Shifts sideways and downward in the counterclockwise direction twice.

D1 Alternates between clockwise and counterclockwise rotation around the X-axis twice.

D2 Alternates between clockwise and counterclockwise rotation around the Z-axis twice.

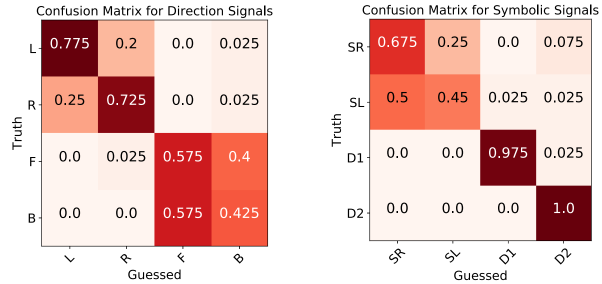
As these signals often share similar rotation axes or motions, it is useful to think of them as pairs.

The order of the two rounds was counterbalanced across all participants. The teaching order was also counterbalanced by pairs.

We recruited 8 participants (3 male, 4 female, and 1 other) with age ranging from 19-33 years old ($M = 23.3$, $SD = 4.2$) from a mid-sized city in the United States for the study. Participants held the device in their dominant hand.

B. Result

1) Magnitude Evaluation: The aim of our first task was to understand participants' ability to distinguish between different torque levels. From the data collected, we found a significant linear regression ($F(1, 31) = 154.1$, $p < .0001$) with R^2 of 0.831. We found that the human hand is very sensitive to the torque generated by the device. Based on the regression, we infer that participants can feel the torque with a change of 4.8 rad/sec^2.



(a) Overall confusion matrix for directional signals

(b) Overall confusion matrix for symbolic signals

Fig. 4: Overall confusion matrices for both classification rounds in the exploratory study

2) Classification Evaluation: We analyzed the participants' classification of the signals by calculating the precision and recall for each individual signal and the macro average of all signals. Precision measures the ratio of the correct guesses among all guesses for that signal, whereas recall measures the ratio of true signals that were guessed correctly. The F1-score reports the harmonic average of precision and recall. All results are shown in Table I.

TABLE I: Analysis of participants' classifications in the exploratory study

Directional			
Type of Feedback	Precision	Recall	F1-Score
Left	0.76	0.78	0.77
Right	0.76	0.73	0.74
Forward	0.5	0.58	0.53
Backward	0.49	0.42	0.45
Average	0.63	0.63	0.62

Informational			
Type of Feedback	Precision	Recall	F1-Score
SR	0.57	0.68	0.62
SL	0.64	0.45	0.52
D1	0.98	0.98	0.98
D2	0.88	1.0	0.94
Average	0.77	0.78	0.77

C. Insights from the Study 1

The results were mixed because the participants had an easier time distinguishing some signals relative to others. As shown in the combined confusion matrix, all participants (Figure 5), participants tended to mistake mirrored signals (clockwise or counterclockwise) along the same axis of rotation. Participants were very good at distinguishing signals with different rotational axes. However, participants tended to identify both *Forward* and *Backward* as *Forward*. Similarly, participants frequently incorrectly classified *SL* as *SR*. It appears that participants may have been randomly guessing between these and tended to favor either *Forward* and *SR*. One possible explanation for bias towards *Forward* and *SR* is the ordering effect of the training. Participants were shown

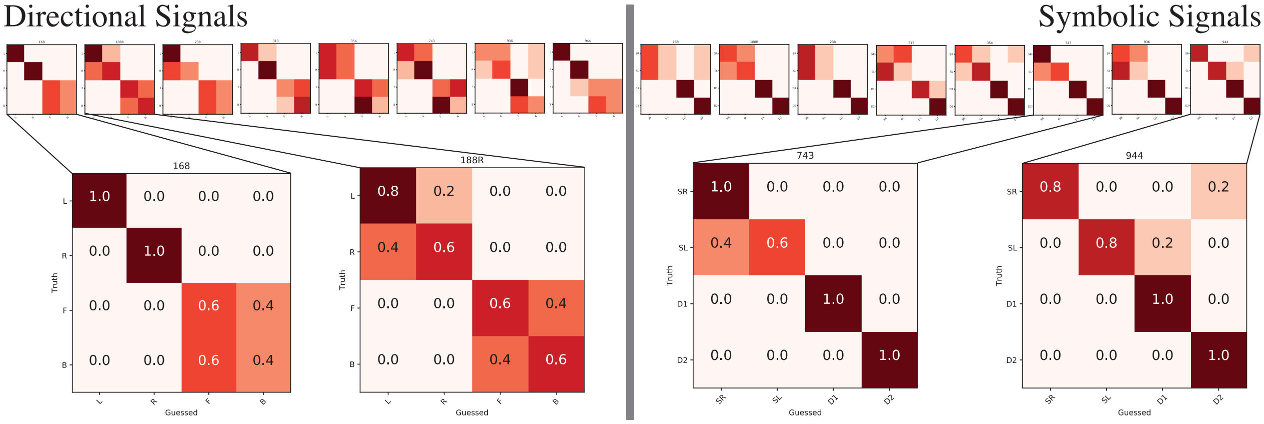


Fig. 5: Each participant's individual confusion matrix from the exploratory study is shown above. As shown, some participants were more successful at distinguishing between mirrored signals.

both *SR* and *Forward* first during the learning phase. Another possibility is that there may be a biomechanical effect within the human hand and wrist that biases sensation in these directions. In subsequent analyses, we also found a drift in heading as the study progressed. Our second study was designed to better understand the causes of this divide and solved some technical issues found in the first study.

While the averaged results seemed to be mixed, some participants were able to distinguish different clockwise and counterclockwise spins (Figure 5, right). For example, participants 743 and 944 were rather accurate at classifying both *SR* and *SL*. While *Forward* and *Backward* were more challenging, participant 743 seemed to distinguish the two different signals but attributed them incorrectly. This suggests that some people may be quite good at perceiving these signals. As this is a novel interaction technique, we also believe some of the incorrect classification seen in all participants could be attributed to the limited training and performance could be improved with mastery of the device.

VIII. User Study 2 - Haptic Recognition

A. Study Tasks and Participants

For the second user study, we used the same directional signals for task 1 but refined the design. Instead of switching between the Y-axis and Z-axis as axis of rotation to represent different directions, all the directions were conveyed through the same forward upward rotation with the axis of rotation being parallel to the ground in the X-Y plane. The device first oriented itself to face the direction in the world frame before rotating upwards and sending a pseudo-rotation in the upward direction twice. While holding onto the device, the user would feel the generated torque moving their hand forward and upwards in the chosen direction.

Participants first experienced the signals 8 times (4 in order followed by 4 in random order) before a practice round where they were tested and told the correct answers. They were then given the signals one more time in order and were allowed to replay any signal they wanted. The study then moved to the evaluation phase, where participants experienced 24 signals (6 per direction in random order).

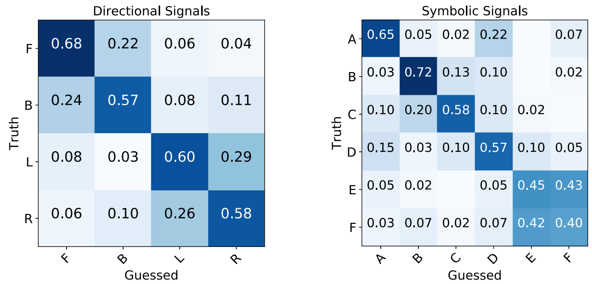
Task 2 evaluated 6 different symbolic signals, modified from the first user study. They were:

- **A** Alternate between clockwise and counterclockwise pseudo-rotation around the Z-axis twice, similarly to D1 in Study 1;
- **B** Alternate between clockwise and counterclockwise pseudo-rotation around the X-axis twice, similarly to D2 in Study 1;
- **C** Same movement as A but at half speed;
- **D** Same movement as B but at half speed;
- **E** Clockwise pseudo-rotation around the Z-axis twice, similar to the Forward direction signal in the Study 1; and
- **F** Counterclockwise pseudo-rotation around the Z-axis twice, similar to the Backward direction signal in the Study 1.

As we wanted to evaluate the intuitiveness of the gestures, we told the participants that all of the signals were different but chose not to inform them of exactly how each signal was distinct. Participants were first shown the 6 signals 3 times (2 in order and 1 in random order), followed by a practice round where they were told the correct label after each guess. They were then shown the signals in order twice, followed by another practice round of 12 signals. Next, they were then shown the gestures once and were allowed to replay any signal they wanted. Finally, participants completed an 18 round evaluation phase (3 per symbol in random order).

The order in which participants learned the signals was counterbalanced according to the axes of rotation (for example the signal *forward* and *backward* were counterbalanced as they are from the same axis of rotation). We also counterbalanced the pairs similarly in Task 2.

We recruited 12 new right-handed participants (8 females, 3 males, and 1 other) ranging in age from 20-26 years old ($M = 23.1$, $SD = 2.3$) from a mid-sized city in the U.S.



(a) Overall confusion matrix for directional signals

(b) Overall confusion matrix for symbolic signals

Fig. 6: Overall confusion matrices for participant guesses

B. *Classification Results*

TABLE II: Analysis of Directional Movements

Directions	Precision	Recall	F1 Score
Forward	0.64	0.68	0.66
Backward	0.62	0.57	0.59
Left	0.60	0.60	0.60
Right	0.57	0.58	0.58
Average	0.61	0.61	0.61

1) Directional Movements: To evaluate whether participants were able to discriminate directions, we calculated the precision, recall and F1-score for each direction. (See Table II.) A confusion matrix showing the share of guesses for each direction is shown in Figure 6a. It remained challenging for users to distinguish between signals that rotate along the same axis. For *Forward* signals, participants guessed either forward or backwards 90% of the time. A similar trend can be seen in the other directions. Again, performance varied dramatically between users: some participants (13, 18) were more successful than others (Figure 7).

2) Symbolic Signals: We calculated the precision, recall score and F1-scores for each signal and reported them in Table III. To better interpret the result, a confusion matrix for all signals is shown in Figure 6b.

TABLE III: Analysis of Symbolic Motions

Symbols	Precision	Recall	F1-Score
A	0.64	0.65	0.64
B	0.66	0.72	0.69
C	0.69	0.58	0.63
D	0.51	0.57	0.54
E	0.46	0.45	0.45
F	0.41	0.40	0.41
Average	0.56	0.56	0.56

While we again see a trend where participants were able to distinguish symbols, the errors were diffuse across the symbols. The ability to distinguish between different signals varied widely among the different participants (Figure 7).

C. *Other Findings*

Three survey questions about the participants' comfort when holding the device were reliable (Cronbach's $\alpha = 0.8095$), and participants rated the device an average score of 2.1 ($SD = 1.15$) on a 7 point scale where lower was more comfortable. This result suggests that participants did not find the device uncomfortable, which is promising for future applications.

We also asked whether participants would like more time to become familiar with the device. Participants provided an average rating of 5.96 ($SD = 1.3$) where high meant more time was required. This reinforced our belief that learning is an important factor in whether participants can differentiate these types of haptic signals.

Participants also felt that the symbolic signals were easier to identify ($M = 4.25$, $SD = 1.54$) compared to the directional signals ($M = 4.00$, $SD = 1.65$), as evaluated using a repeated-measures ANOVA ($p = .0435$). This result could be attributed to two factors. First, participants may have found the symbolic signals easier to distinguish compared to the direction symbols. Alternatively, participants had more experience with the device by the time they started Task 2.

IX. Discussion

One of the strongest findings across both studies is the importance of individual differences: some participants are inherently better than their peers at discriminating haptic signals. These high-performing individuals could utilize a rich set of ungrounded kinesthetic haptic interactions. While our improved method of conveying directions in the second user study performed slightly worse on average, the best performing participants were able to pick out nearly all of the signals compared to their high-performing peers in the first user study who were not able to. The change in interaction design to rely on only distinguishing different axes proved to be more suitable than using both axis and rotational direction at the same time. However, there are still users who have difficulty with these haptic interactions. Below, we explore how future work could improve performance for a wider range of users.

A. *Role of Learning*

Even with the substantial instructional time increase in the second study, some participants still struggled with identifying different haptic signals. For the six signals we explored in the symbol section, participants were more successful in distinguishing the first four signals (A, B, C, D), which moved similarly but had different timings. In both studies, participants were unable to discriminate well between a pair of signals that moved clockwise and counterclockwise rotations along the Z-axis in the base frame. This difficulty might be attributed to the lack of familiarity with these types of interactions because most people lack exposure to similar haptic signals in their daily lives. Commercial products that use haptic interaction beyond binary signals remain sparse and highly specialized to specific domains. An interesting future direction would be to explore whether a more robust learning protocol would lead to better results. As seen in dexterous hobbies and sports, humans can develop high-precision tactile and haptic sensing over time.

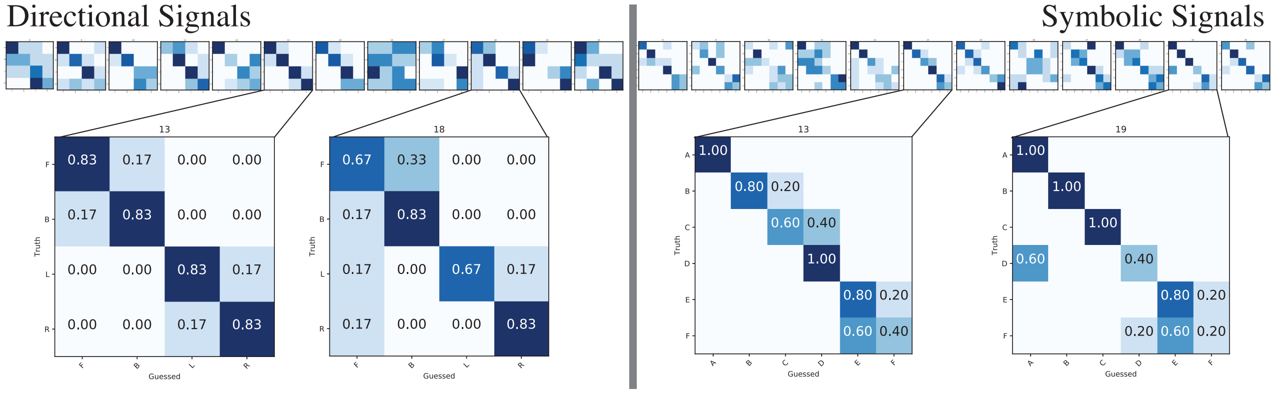


Fig. 7: Confusion matrices for each participant in the second user study are shown above. As shown, some participants (13, 19, etc.) were better at distinguishing between different signals relative to others.

The method of training could also be a factor. To test this, an alternate learning protocol was tested with two extra participants for Task 2 of the user study. Instead of simply asking them to find the differences between the signals, the experimenter explained what differentiated the signals from each other. These participants had 70% and 95% success, respectively, in classifying different symbolic signals. While this implies that a more direct method of teaching could help, exploring a robust and useful method of instruction requires considerable follow-up effort. The initial, exploratory work presented here suggests that there are viable opportunities within this domain. We believe that future studies should examine alternative teaching strategies for novices and metaphors of haptic experiences in daily life. Detailed demographic questions on relevant hobbies, sports, and job duties may also be useful in explaining why some people are high performers.

B. Spherical Robot Design

The spherical design of the robot posed an additional challenge. A spherical form welcomes users to grasp the robot regardless of the initial orientation. Participants in both studies asked how to grasp and hold it. Compared to other, directional haptic devices, a spherical shape has no specific orientation and must be designed to start working in any orientation or grip. The device must figure out the orientation of the grasp and generate appropriate feedback.

The grasp of the user can be estimated through the embedded sensors inside the robot. While we were unable to estimate the yaw value (where the device is facing perpendicular to gravity) with the internal sensors, rough estimations can be achieved through structure calibration interaction. Adding additional sensors such as magnetometer or proximity sensors could also help.

Our study focused on using kinesthetic haptic signals in the spherical form. Other forms, such as tactile haptics, could be generated by embedding multiple actuators on the surface of a spherical device and vibrating each unit independently. Whether users could detect and distinguish different tactile vibrations would be an interesting question for future work.

X. Potential Use Cases

While there is room for improvement, we believe this exploratory work successfully demonstrates potential value, especially for users who rely on sensory inputs other than vision and hearing. We also believe our findings could be applied using universal design principles to provide value in broader populations, job tasks, and applications. In this section, we focus on how these interactions might help people who are blind or low vision.

A. Navigation + Hazard Encoding

We believe this approach has potential for guiding people who are blind or low vision, as well as the general population, to their destinations [18]. The directional signals in the user study could easily point users towards various headings. Combined with a smartphone for localization, this approach could provide eyes-free guidance, especially in locations where looking at a phone is undesirable (e.g., in crowds, poor weather, etc.). For simple cases, pulses towards left and right could signal upcoming turns with a growing pulse rate when nearing an intersection and continuous pulsing at intersections. Beyond simple directions, the diversity of signals could support a wide and intuitive encoding of movements. For example, a pulse upwards relative to the user could signal an upcoming half step or change in flooring. A continuous pulsing upwards could also be used to indicate an upcoming staircase and whether it goes up or down. We could also encode other common obstacles, such as doors, with distinct signals such as the left-right alternating pulsing used in the user study.

B. Lane Keeping

Another challenge faced by people who are blind or low vision is maintaining a straight line when walking forward. When paired with a phone for localization [19], our approach could provide guidance when the user slowly drifts out of their virtual lane. When drift is detected, the system could pulse clockwise or counterclockwise to nudge the user back to the center. This signal could be expressed in a different axis to disambiguate it from left/right turn signals during navigation. This interaction cannot be done using prior haptic systems without overloading an existing signal.

C. Clock and Silent Timer

Linked with mobile apps, our approach could be used as a timer to communicate a countdown for upcoming buses and vehicles. Knowing when to exit a shelter so a bus does not pass without stopping is a stated need within the blind and low vision community [20]. Likewise, alarms could be used to alert when to exit a transit vehicle.

D. Computing Application Interfaces

Expanding upon prior work [3], kinesthetic haptic interactions could be integrated into spherical GUI robots. This capability could extend the binary nature of the haptic described in prior work and provide a richer haptic space for expressing additional information. For example, a left-right alternating signal and up-down signal could indicate illegal and possible operations, respectively (yes/no), when using the GUI robots as a cursor.

XI. Conclusion

In this paper, we explored extending haptic interaction capabilities to a spherical educational robot. The results suggest promise for this approach: participants were able to differentiate among different signal designs and strengths. Training remains an open question due to large variations in participant performance; some participants illustrated strong performance while others struggled. The results also demonstrate the feasibility of using this robot in place of custom-built haptic displays. Future work is needed on generating better perceptible signals, using additional semantic labels for information signals, and confirming the impact and value of this exploratory approach in real-world applications. A robust and useful training methodology is also needed to support users who have difficulty in recognizing different signals.

XII. Acknowledgements

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