2-DOF Contact Location Display for Manipulating Virtual Objects

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ABSTRACT

A novel, low inertia, two degree-of-freedom (2-DOF) contact location display (CLD) device has been designed, prototyped, and tested. This device positions a small spherical contactor beneath the user's fingerpad at the point of contact between the finger and a virtual surface. Kinesthetic forces are provided by a custom haptic device attached to the CLD. The contactor is remotely driven by push-pull wires to reduce the effective inertia of the device at the user's fingertip; however, this design results in significant mechanical backlash. This backlash is characterized and partially compensated for in software. An experiment was used to evaluate several methods of rendering tactile feedback, each using a different method of prepositioning the contactor. The results show no statistical performance differences between rendering conditions. However, a post-experiment survey shows that participants perceived contact location + kinesthetic feedback as more realistic than pure kinesthetic feedback.

KEYWORDS: Haptic rendering, tactile devices and display, virtual environment.

INDEX TERMS: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O; J.4 [Social and Behavioral Science]: Psychology

1 INTRODUCTION AND BACKGROUND

Kinesthetic (force) and tactile (cutaneous) feedback provide important cues when exploring or manipulating objects with our hands. Without tactile information, it is hard to perform simple tasks like typing on a keyboard or grasping a pen. The tactile information provided when touching an object informs us about the local characteristics of the contact (e.g., texture, curvature, and temperature) [1]. Thus, when rendering virtual environments, providing tactile feedback in addition to kinesthetic feedback can enhance the user's ability to explore and manipulate virtual objects [2], [3].

There have been numerous successful efforts in providing haptic kinesthetic feedback cues to a user's finger or hand. Good examples of these devices include SensAble Technology's Phantom and Force Dimension's Omega which display interaction forces through interfaces such as a thimble, stylus, or handle. One drawback of these types of devices is that they cannot render local contact properties. Many studies have investigated tactile device designs to provide local contact properties in a natural and intuitive way.

One such design for providing tactile feedback is a pin array device. Individual pins are positioned by a series of actuators to mimic the local profile of a virtual surface (e.g., [4]). While these devices are efficient at conveying tactile information, they are typically large, heavy, and complex due to a high pin density requirement. These properties make it difficult to mount them to kinesthetic feedback devices. Thus, pin array devices have mostly been tested in isolated tactile feedback conditions. Despite these difficulties, Sarakoglou et al. recently combined a compact 4x4 pin array with an Omega7 kinesthetic feedback device [5]. Their preliminary experiment shows that providing both tactile and kinesthetic feedback cues improves a user's performance in a contour-following task during teleoperation.

Encounter-type haptic devices were developed to provide the intuitive sensation of making and breaking contact. Yoshikawa and Nagura present a good example of an encounter-type device [6]. In their design, the user's finger is placed inside an oversized thimble attached to a kinesthetic feedback device. Using optical sensors around the finger, the device follows the finger without making physical contact with it until necessary. Like pin array devices, this encounter-type design is large and complex.

Kuchenbecker et al. developed a very simple and compact passive tactile display device called the Touch Thimble [7]. Like Yoshikawa's design [6], the user's finger is placed inside a relatively large thimble mounted on a Phantom. The base of the finger is connected to the thimble via a series of compliant foam springs. When contact is made with the virtual environment, the rendered forces push the thimble into contact with the user's finger. Their shape recognition experiment, while showing no benefits of adding the Touch Thimble to the Phantom interface, suggested that some users preferred to use this device over the conventional Phantom thimble.

Some researchers hypothesized that the orientation of contact can also contribute to shape recognition of virtual objects [3], [8]. Dostmohamed and Hayward used a 2-DOF spherical mechanism that orients a plate to match a virtual surface at the point of contact. It was shown that rendering the orientation of contact, even in the absence of the kinesthetic cues, provides the same curvature discrimination threshold on virtual surfaces as on real surfaces [8]. Frisoli et al. extended this work by miniaturizing the tilted plate design and designing their device to also make and break contact with the user's fingertip [3]. The tactile plate is remotely controlled using sheathed wires to reduce the effective mass at the fingertip. However, limitations due to the large size of the device and its complexity make it difficult to be integrated with commercially available kinesthetic feedback devices such as a Phantom. Instead, the tactile interface is attached to a custom kinesthetic feedback device with limited mobility. Using a curvature discrimination task, they demonstrated that providing both tactile and kinesthetic feedback information improves shape perception.

Chinello et al. developed a similar tactile device using a small tilting plate beneath the fingerpad to provide the contact force in different directions [9]. Using two of these tactile displays for the

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IEEE World Haptics Conference 2013
14-18 April, Daejeon, Korea
978-1-4799-0088-6/13/$31.00 ©2013 IEEE

index finger and thumb, Prattichizzo et al. conducted a virtual needle insertion experiment [10]. They reported no noticeable difference in performance in the insertion task between the tactile only and combined tactile and kinesthetic feedback conditions.

Provancher et al. developed the contact location display (CLD) with the aim of having a simple and intuitive device to provide both tactile and kinesthetic feedback information [11]. This device renders the point of contact with a virtual object along the proximal-distal direction of the finger (i.e., a 1-DOF mechanism) and was developed for use in planar environments.

This paper presents research that is an extension of the previous 1-DOF contact location display (CLD), which was used for investigating curvature discrimination, contour following, etc. [11]. The contributions of the work presented in this paper are twofold. The paper's first contribution is the design of a novel 2-DOF CLD device capable of rendering the contact location between the finger and a virtual object in both the ulnar-radial and proximal-distal directions using a spherical 5-bar mechanism worn on the user's finger. This additional degree of freedom enhances interactions with 3D virtual objects over the prior 1-DOF CLD. The mass and inertia of the device are kept low by using push-pull wires and a remote actuator box to permit integration with a kinesthetic feedback device, allowing both tactile and kinesthetic feedback to be rendered simultaneously.

The second contribution of this paper is the creation and evaluation of tactile rendering conditions that utilize foreknowledge and prepositioning of the CLD's contactor to enhance interactions with the virtual environment. Interestingly these enhanced interactions are judged by users as "more realistic" than conventional rendering schemes.

In the remainder of this paper, we present the design, characterization, and compensation of our novel 2-DOF contact location display. We then present experiments for evaluating user performance with this device under different tactile rendering conditions in a simple manipulation experiment and discuss the results of this experiment.

2 Device Design

Figure 1 shows our 2-DOF contact location display (CLD) prototype mounted via a passive 3-DOF gimbal onto a custom kinesthetic feedback device (with capabilities similar to a Phantom Premium 1.5). The 2-DOF contact location display device consists of two components: 1) a thimble with a spherical contactor and 2) an actuator box. The contactor at the thimble is driven through two push-pull wires connected to the actuator box. Further details of each portion of the device follow.

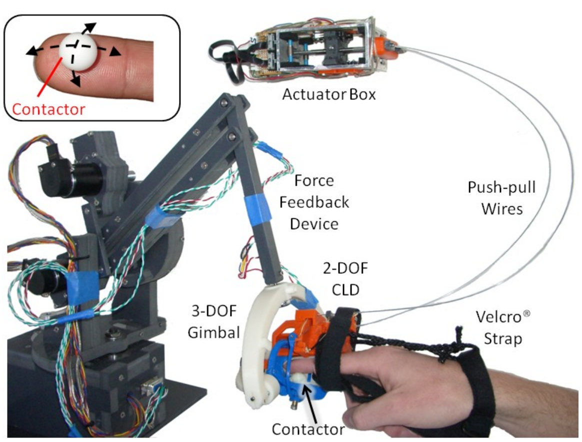

Figure 1. 2-DOF contact location display (CLD) device. The inset image in the upper left shows the degrees of freedom that the CLD is capable of moving the contactor. The actuator box is supported by an overhead support structure (not shown).

2.1 Thimble and Spherical Mechanism

The thimble mounts securely to a user's index finger using two finger restraints, one placed at the fingertip, and a second at the base of the finger (Figure 2). A Velcro® strap is used to prevent the finger from pulling out of the thimble. Transparent tape is shown in place of this Velcro strap in Figure 1. A spherical 5-bar mechanism has been integrated with and mounts to the thimble. This 5-bar mechanism translates the linear motion of the push-pull wires into spherical motion of the contactor. This mechanism decouples the proximal-distal and ulnar-radial contactor motions while still providing a high structural stiffness for maintaining contactor positioning accuracy. This spherical 5-bar design has been utilized in several earlier haptic devices such as the kinesthetic feedback Immersion Impulse Engine 2000 joystick and the tilting plate tactile feedback display devices presented in [3] and [8]. The thimble and the 5-bar mechanism are rapid prototyped using fused deposition modeling (FDM) of ABS plastic material. The thimble mass is about 0.1 kg and has a bounding box of 85 x 80 x 60 mm.

The proximal-distal motion of the spherical mechanism is driven directly by one of the push-pull wires. The ulnar-radial motion is driven by the second push-pull wire though a loop of low-stretch fishing line. Both push-pull wires enter the thimble adjacent and parallel to each other, which allows the user to orient his/her finger with reduced mechanical restrictions.

The contactor (tactile element) is a plastic sphere with a diameter of 9.5 mm. The workspace of the contactor beneath the finger is about 12 mm arc length both in the ulnar-radial and proximal-distal directions. A spring-loaded arm on the spherical mechanism accommodates the difference in finger curvature in the distal and lateral directions, as well as the variations in finger sizes between users, to keep the tactile element in contact with the user's finger. The nominal contact force is about 0.3 N and the equivalent spring stiffness is less than 0.1 N/mm. In addition, the contactor can freely rotate within a spherical cavity, which reduces the force required to drive the system.

It should be mentioned that while prior versions of the contact location display are capable of making and breaking contact, we have chosen to omit this feature and present a mechanism as simple as possible in the present design while evaluating the efficacy of the proposed 2-DOF CLD. Future revisions may again consider adding this feature.

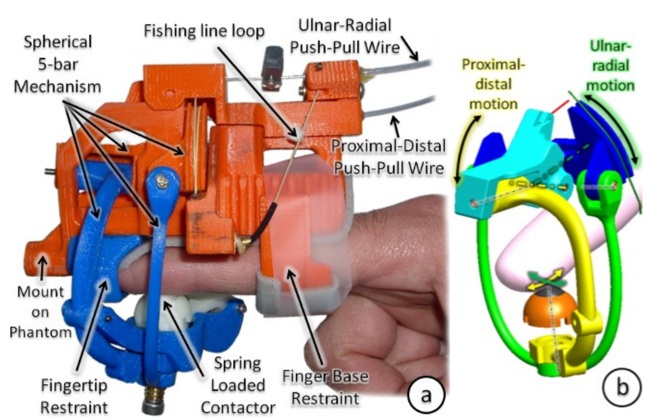

Figure 2. Contact location display device: (a) on a user's index finger, (b) axes of rotation of the spherical 5-bar mechanism.

2.2 Push-pull Wires and Sheaths

The push-pull wire is made from 0.61 mm diameter spring steel wire and is passed through flexible sheathing made of Teflon® (PTFE). The teflon sheathing has inner and outer diameters of 0.79 and 1.59 mm, respectively. Each push-pull wire and its sheathing are about 640 mm long and are deformed into a U-shape to allow for unrestricted finger motion of the thimble (see Figure 1). Although the sheathing is flexible and easy to bend, its overall high axial stiffness (2700 N/m) makes it reasonably suitable for a low backlash system when combined with a push-pull wire of proper diameter.

2.3 Actuator Box

A custom actuator box was designed and manufactured in order to independently drive the two push-pull wires. Each push-pull wire is connected to a corresponding linear motion carriage driven by a 3.18 mm pitch lead screw. Two Maxon RE16 motors with 4.4:1 planetary gearboxes provide the independent motion of the leadscrew drive systems via helical couplers. The position of each push-pull wire is determined by its motor's encoder which results in a resolution of ~0.01 mm at the output of the leadscrew.

The actuator box is mounted on a stationary frame (Figure 1) instead of on the user's forearm as in the previous design [11]. This choice further reduces the perceived mass and inertia of the device as well as simplifies the donning of the apparatus.

3 Characterization and Backlash Compensation

In order to evaluate the performance of the device, the backlash was measured in-situ for motions of the contactor similar to those seen in normal manipulation. The contactor's position was measured using two orthogonal linear optical encoders (PE-500-2-I-S-L), which have a 12 µm resolution. Uncompensated, the backlash was found to be 5.2 mm and 6.1 mm for the proximal-distal and ulnar-radial directions, respectively. These values slightly increase when a finger is inserted into the device.

A recent, yet to be published, study conducted in our lab indicates that participants are able to detect backlash of less than 1 mm along their fingerpad during active exploration of curved surfaces [12]. We have implemented software to compensate for our device's backlash by adding/subtracting a fixed offset value to the desired position of the contactor whenever its direction of motion reverses. This fixed offset is less than the full backlash of the system to prevent unrealistic sudden jumps in position due to uncertainty in the configuration dependent backlash. After compensation, backlash was reduced from 5.2 to 3.5 mm and 6.1 to 3.1 mm in the proximal-distal and ulnar-radial directions respectively.

Inserting a finger into the device induces extra drag force, which increases the backlash levels by ~0.5 mm. Figure 3 shows the relationship between the commanded proximal-distal desired position and the actual contactor position for both the uncompensated system and the partially compensated system. While this performance isn't perfect, and certainly more sophisticated backlash compensation schemes could be employed, the device performance is more than capable of representing rolling contacts with virtual objects to a user. We therefore decided to proceed with evaluating the effects of providing contact location feedback in a simple manipulation task. More sophisticated backlash compensation schemes such as the "standard" or "improved dual-loop" schemes [13] may be revisited in the future. However, these schemes require mounting an appropriate position sensor closer to the contactor, which would make the thimble heavier and more difficult to package.

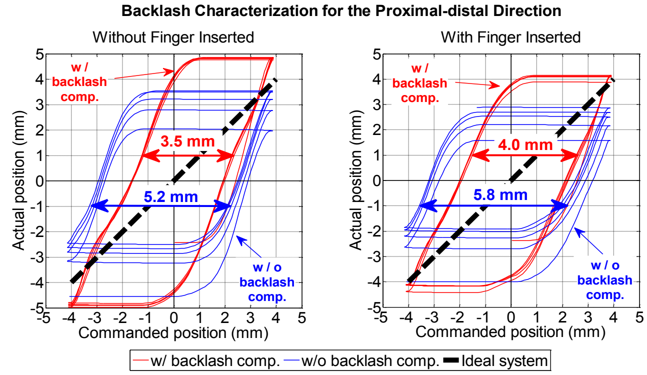

Figure 3. Proximal-distal backlash characteristics of the device with and without a finger inserted. The dashed black line shows an ideal system. The span of the blue arrows indicates the device's uncompensated backlash and the span of the red arrows indicates the compensated backlash.

4 Methods

Our hypothesis is that rendering contact location using our 2-DOF contact location display will provide a more immersive virtual environment to the user and improve his/her performance when manipulating and recognizing virtual objects. A virtual ball manipulation experiment was used to evaluate this hypothesis. The experiment was designed to force participants to use both the proximal-distal and ulnar-radial motions of the contactor by manipulating a virtual ball through a simple maze. Participants were instructed to roll (manipulate) the ball through the maze as quickly as possible while minimizing the amount of contact between the ball and maze walls.

During the experiment, the testing apparatus was obscured by a cloth to prevent visual feedback. White noise was played over headphones to block all auditory feedback and reduce distractions. Experiment instructions were displayed on the computer screen (see Figure 4).

The ball manipulation task was performed under five different haptic rendering conditions (see Table 1 in Section 4.3). Different experiment environments were considered in order to have a range of difficulty levels for the task and to discern which environment condition is most suitable for future device evaluations. These environments included diminished visual feedback modes and use of vibration feedback (superimposed sinusoidal vibration onto the kinesthetic feedback in order to indicate contact with the wall of the maze). In this paper we only

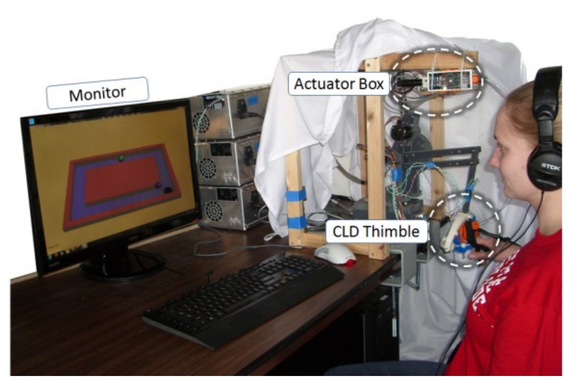

Figure 4. A participant manipulating a virtual ball using the developed 2-DOF contact location display and kinesthetic feedback.

focus on the environment with only kinesthetic and contact location (i.e., no vibration and no visual feedback) as it provides the greatest contrast in results among the different environments.

The experiment was divided into two sessions, each consisting of 20 trials (40 trials total). Each session lasted about 60 minutes with a small break half way through to reduce muscle fatigue. All five tactile rendering conditions were presented in each session. A Latin Squares reduction was used to determine the order in which the conditions were presented to each participant. This reduced the number of permutations needed for balanced testing.

The experimental protocol was approved by the University of Utah IRB.

4.1 Participants

Eight naïve volunteers (7 male, 7 right-handed) with a mean age of 27 and standard deviation of 7 years participated in the experiment.

4.2 Virtual Environment

The virtual environment is composed of a virtual ball, a virtual finger, and a rectangular perimeter maze with a length and width of 180 mm and 105 mm, respectively (Figure 5).

The perimeter maze consists of a channel around the edge of the workspace formed by 10 mm high walls with a 25 mm channel width. The maze dimensions were determined in a pilot study and create a reasonable level of difficulty in the task. The maze walls are rendered kinesthetically only (the rendered contact location does not consider the collision with the maze walls) to avoid problems arising from having to render multiple points of contact. The starting location and direction of ball manipulation for each trial is chosen randomly from a list of eight possible combinations to minimize potential learning effects for repeated motions. The start and end points of the maze are placed adjacent to each other in one of the four corners of the maze so that the total path length (560 mm) remained the same across all trials. A wall between the start and end points prevented participants from moving the ball in the incorrect direction.

The virtual finger is modeled as a sphere with a diameter of 13 mm, approximating the diameter of a human finger. The virtual ball's size (16 mm in diameter) is chosen to be manipulatable under all tactile rendering conditions (including kinesthetic feedback only condition) to prevent having an undesired biased result from our evaluation. Contact with the virtual ball is rendered both kinesthetically and tactilely to participants, as appropriate to the respective rendering condition. The ball is modeled assuming perfect rolling conditions (no slip) in order to ensure the contact location cues are used during manipulation. In other words, the no slip condition prevents participants from simply pushing/sliding the ball along a maze wall. Friction is rendered between the ball and maze wall to act as a penalty for making contact with the wall that slows the participants' progress and also to allow the participants to better sense this contact.

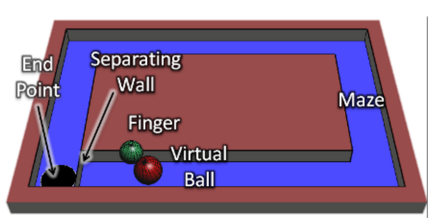

Figure 5. The virtual environment. During the experiment, the finger and virtual ball are invisible and only the top view of the maze environment was shown to participants.

Table 1. Haptic rendering conditions (C1-C5).

	Feedback Conditions
C1	Kinesthetic feedback only
C2	Kinesthetic feedback + CLD with no prepositioning
C3	Kinesthetic feedback + CLD with 30 mm prepositioning
C4	Kinesthetic feedback + CLD with 30 mm hybrid prepositioning
C5	Kinesthetic feedback + CLD with prepositioning always

4.3 Tactile Rendering Conditions

In an encounter-type haptic device, the contactor is prepositioned close to the contact point before making a contact. However, since the contactor of our device is always in contact with the finger, we considered two general scenarios for rendering the contact location when a contact is made. In the first scenario, the contactor position is updated at the moment of contact. This sharp motion may negatively affect participants' perception and performance when initiating a contact. In the second scenario, the contactor is prepositioned continuously. However, this continuous motion while in free space may distract participants.

Based on these two scenarios, five different tactile rendering conditions are formulated for this study: (C1) kinesthetic feedback only (non-CLD), (C2) CLD with no prepositioning, (C3) CLD with prepositioning when the user's finger is within 30 mm of making contact, (C4) CLD with 30 mm hybrid prepositioning (to be explained below), and (C5) CLD prepositioning regardless of distance from the surface of the ball. The 30 mm threshold used in C3 and C4 was found in a pilot study to be slightly larger than the average distance between the ball and finger during manipulation. Table 1 summarizes the above rendering conditions.

During C2, the contactor does not move until the finger makes contact with a virtual object. During C3, the contactor is continuously prepositioned while the finger is within 30 mm of the surface and the contactor returns to the center of the fingerpad when the finger is outside of this range. This condition takes the weighted average of the closest point of contact with the virtual object and the contactor's centered position, where the weighting of the center position goes to 100% at 30 mm from the object. The hybrid prepositioning in C4 behaves similar to the prepositioning in C3 with the exception that once the distance between the user's virtual finger and the virtual object exceeds 30 mm, the contactor position will remain centered (i.e., does not update as in condition C2) until a contact has been made with the surface again. This was done to remove the distraction of contactor prepositioning when the user was moving in free space, while providing the benefit of contactor prepositioning during manipulation, which helps with directional localization of the ball.

4.4 Experiment Task

Participants manipulate the ball through the maze in each of the five tactile rendering conditions (C1-C5) under six visual and vibration feedback environments, including with no visual feedback. Within each trial, participants are given 60 seconds to roll the ball as far through the maze as possible. Total travel distance is recorded for those who did not complete the maze and total time is recorded for those who did.

Without any form of visual feedback, it is possible for participants to lose track of the ball. They could request "help," by pressing the spacebar on the keyboard, which would allow participants to temporarily see the location of the finger and the ball. Providing the "help" option prevents participants from spending too much time searching for the ball rather than accomplishing the actual required task—manipulating the ball. Both the ball and virtual finger become invisible again after a contact is made with the ball. Participants are informed that requesting "help" will act as a penalty in their task completion score.

At the end of the second test session, participants are asked to fill out a survey. This survey helps to determine the participants' opinions of the rendered tactile feedback conditions. The survey asks participants to judge the different tactile conditions individually while they actively switch between and briefly experience each condition again. Participants are asked to move the ball at least around a corner without visual feedback to focus on the aspect of the tactile rendering when filling out the survey. They evaluated the rendering conditions based on a 5-point Likert scale ('strongly disagree' to 'strongly agree'). If two different rendering conditions feel the same to the participants, they are instructed to select the same level response for both conditions. Survey questions are randomized and asked in both a positive and negative sense to avoid bias.

5 Results and Discussion

Of all six combinations of visual and vibration feedback presented in the experiment, the results from the environment with no visual or vibration feedback show the greatest contrast among the rendering conditions. Therefore, for brevity, we only present our results for the test environment that did not provide visual or vibration feedback for this conference paper.

5.1 Objective Results

The important objective metrics in our experiment include: 1) how fast participants manipulated the ball, 2) how many times the ball contacted the maze, and 3) how many times participants requested help.

Figure 6a shows the mean and 95% confidence interval of average speed of the ball under different tactile conditions C1-C5. The average speed is computed as the distance the ball traveled along the center-line of the maze divided by the completion time. The results show that all conditions have an average speed of about 6 mm/s. A within-subjects one-way ANOVA shows no statistical differences among the tactile conditions [$F(4,75)=0.22$, $p=0.92$].

Figure 6b shows the mean and 95% confidence intervals of the number of ball–maze contacts for each rendering condition. No statistical differences among the rendering conditions were found [$F(4,75)=0.46$, $p=0.76$]. This may be because the information provided through the 2-DOF CLD device was redundant with that provided kinesthetically and thus was not required during such gross manipulation. Lederman et al. also hypothesized that the partial success of participants in a shape recognition task with impaired tactile feedback might be due to additional kinesthetic feedback cues provided to participants [2].

Figure 7 shows the mean and 95% confidence intervals of the number of times help was requested to find the location of the ball

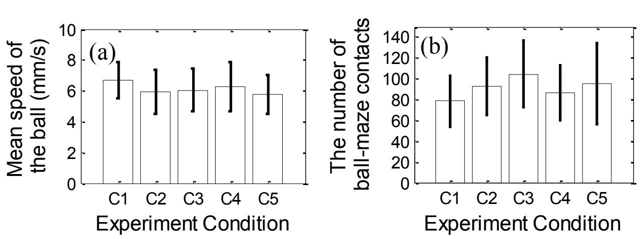

Figure 6. Results for maze environment under rendering conditions C1-C5 without vision or vibration feedback. (a) Mean speed of the ball. (b) Mean number of ball-maze contacts. Error-bars are 95% confidence intervals.

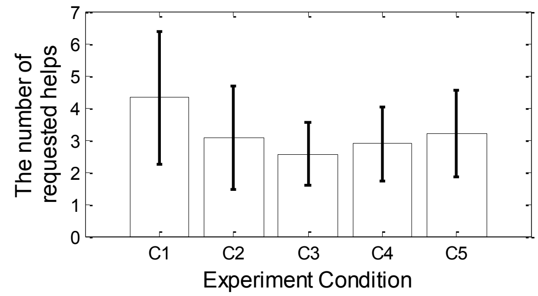

Figure 7. Mean of number of times participants requested help under rendering conditions C1-C5 (for the environment condition without vision or vibration feedback). Error-bars are 95% confidence intervals.

with the finger. Although there is no significant difference among the conditions [$F(4,75)=0.92$, $p=0.46$], the data indicates less help is required when using the CLD for localizing the ball (or losing track of the ball's location). On average, participants requested help the least number of times on average during tactile rendering condition C4 (30 mm hybrid prepositioning) while help was requested the most under C1 (kinesthetic feedback only).

5.2 Subjective Results

The important metrics of the survey are: 1) preferred tactile condition and 2) how realistic the participant found the tactile conditions.

The results of the survey are depicted in Figures 8 and 9. This approach of visualizing Likert scale data is known as a net stacked distribution graph with a central base. The central base can show the skewness, non-neutrality, and intensity of responses in an easily read manner [14]. Each colored section represents the number of responses of a specific Likert level. The stronger responses are stacked on the moderate ones. Neutral responses are not shown in the graphs.

Figure 8 shows the participants' preference of use for each tactile condition. Running a Kruskal-Wallis test shows that the use of CLD has a nearly-significant effect on their preference [$H(4)=9.42$, $p=0.051$]. Participants most preferred to interact with the CLD under the 30 mm hybrid prepositioning condition (C4). This is followed closely in preference by the CLD with 30 mm prepositioning condition (C3). On the other hand, kinesthetic feedback only (C1) was the least preferred rendering condition.

Figure 9 shows the response of the participants regarding the realism of the given tactile conditions. The use of the CLD has a

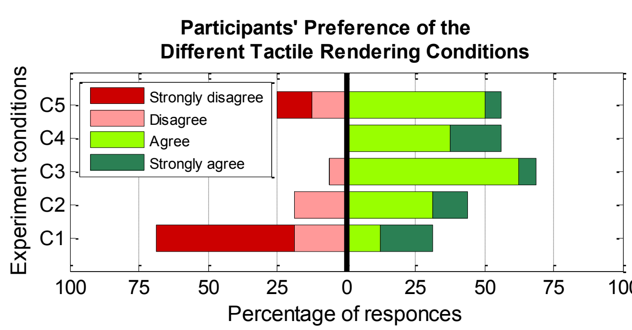

Figure 8. Participants' preference under different tactile conditions. The bars on the left (right) side of the center line show negative (positive) responses. The neutral responses are not shown. Participants preferred receiving contact location information with prepositioning the most.

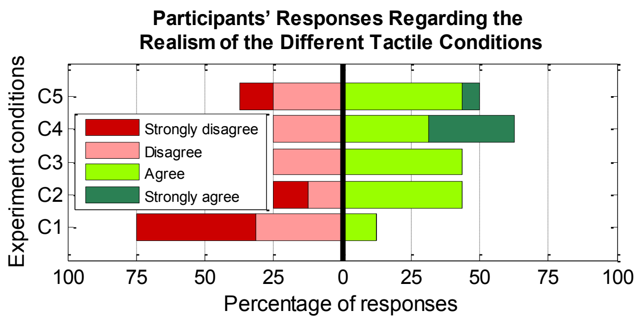

Figure 9. Participants' responses regarding the realism of the different tactile conditions. The bars on the left (right) side of the center line show negative (positive) responses. The neutral responses are not shown.

statically significant effect on the realism [H(4)=16.98, p=0.002] with a mean rank of 21.56 for C1, 41.88 for C2, 43.75 for C3, 53.19 for C4, and 42.13 for C5. Doing post-hoc paired comparisons [15] after the Kruskal-Wallis analysis reveals that only one pair of conditions (C1 vs. C4) felt significantly different in realism [K=7.89, $K_{critical}$=5.60]. Participants felt that 30 mm hybrid prepositioning (C4) provided the most realistic interaction. Participants also felt the kinesthetic feedback only condition (C1) provided the least realistic interaction. Our survey shows that overall the CLD conditions are believed to provide a more realistic interaction than the kinesthetic feedback only condition.

The reason that participants preferred prepositioning conditions (C3-C5) over the no prepositioning condition (C2) may be due to the sudden motions of the contactor in C2. Furthermore, the hybrid condition (C4) only prepositions the contactor when participants manipulate the ball in an interactive fashion. This may make condition (C4) appear more realistic than the other conditions when the participant is moving in free space, since they will not feel contactor motion until they make first contact with an object.

6 Conclusions

We have designed and prototyped a two-degree of freedom (2-DOF) contact location display (CLD) device that can be mounted onto a kinesthetic feedback device. The combined device provides both kinesthetic and tactile cues to potentially improve perception and manipulation of 3D virtual objects. Device backlash is characterized and reduced through software compensation. A ball manipulation experiment was used to evaluate the performance of the device and determine tactile rendering methods that improve performance and immersion.

Contrary to our hypothesis, no significant performance benefits for dexterous manipulation of a ball were shown with the CLD device. However, the addition of CLD information allowed participants to better localize the ball, thus potentially improving manipulation performance in more complex tasks. This was most apparent under the 30 mm hybrid prepositioning condition (C4) compared to the kinesthetic feedback only condition (C1). During the C4 condition the contactor position was not updated until a contact was made between the ball and the finger. After the contact was made, the contactor was prepositioned continuously until the distance between the finger and the ball exceeded 30 mm.

The subjective results of our survey indicate that the 30 mm hybrid prepositioning (C4) was the most preferred and perceived to be the most realistic rendering condition among those tested. Conversely, the condition with kinesthetic feedback only (C1) was reported as the least preferred and least realistic feeling condition.

While the addition of our 2-DOF CLD has not been shown to improve user performance, it provides a more immersive experience and some localization benefits. In future work, we will further evaluate feedback conditions C1, C2, and C4 with a greater number of repetitions in order to obtain stronger statistical results. We would also like to investigate the potential benefits of the 2-DOF contact location display for multi-finger object manipulation.

Acknowledgements

The authors thank Josh Schmeiser for his assistance in manufacturing the device prototype. This work was supported, in part, by the US National Science Foundation under award IIS-0904456.

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