
3D Interactions with a Passive Deformable Haptic Glove

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Abstract

This paper explores enhancing mobile immersive augmented reality manipulations by providing a sense of computer-captured touch through the use of a passive deformable haptic glove that responds to objects in the physical environment. The glove extends our existing pinch glove design with a Digital Foam sensor that is placed under the palm of the hand. The novel glove input device supports a range of touch-activated, precise, direct manipulation modeling techniques with tactile feedback including hole cutting, trench cutting, and chamfer creation. A user evaluation study comparing an image plane approach to our passive deformable haptic glove showed that the glove improves a user's task performance time, decreases error rate and erroneous hand movements, and reduces fatigue.

Author Keywords

Passive Haptics, Augmented Reality, Pinch Gloves, Input Device, Interaction Technique.

ACM Classification Keywords

H.5.2 [Information Interfaces and Presentation]: Graphical User Interfaces—Input Devices and Strategies; I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction Techniques.



Figure 1. The new Passive Deformable Haptic Glove



Figure 2. The original ultrasonic glove as a platform to build the PDH glove

Introduction

We have been investigating new precise methods for 3D data manipulation in both augmented and virtual worlds with an ultrasonic glove [1], see Figure 2. This paper explores the use of a passive deformable haptic (PDH) glove, see Figure 1, that captures data when a user touches physical objects and a force is applied to develop touch-based mobile augmented reality (AR) interaction techniques. Our goal is to improve precision, accuracy, and reduce fatigue for users by leveraging the benefits of a deformable material. Deformable materials physically support users' hands and provide sensory feedback on real-world objects. PDHs are non-rigid objects that can change shape when users apply a force, and the PDH provides a repelling spring-like force feedback [2-4]. We are interested in attaching a PDH device to a user's palm as a one-dimensional distance sensor that provides tactile feedback to the user to improve their spatial understanding and control of depth manipulations. In particular, we wish to support the interactive creation of virtual features that are cut into or extrude from the surface of a physical object, with or without prior knowledge of the physical environment. Without known geometric dimensions of physical objects, virtual object registration is achieved through direct touch and global 6DOF tracking of the user.

Our PDH glove utilizes the Digital Foam sensor [4] as the PDH material. The Digital Foam sensor employs conductive foam that changes resistance when deformed. Previously, Digital Foam has been applied as a covering for physical objects to allow clay-like interactions. Our new device attaches it to a glove worn on the user's hand. This glove-mounted sensor allows the user to perform touch-based interactions on a

multitude of physical objects and surfaces, converting a stationary device into a mobile input device. A full description of the PDH glove is found in [5].

Related Work

Glove-based technologies capture real-time finger movements and gestures with high degrees of freedom. Immersion CyberGloves™ use bend sensors to measure joint angles and capture the finger pose. Pinch glove designs use fabric switches attached to the finger tips [6], for command entry. Piekarski and Thomas [7] extended the pinch gloves with an additional switch in the palm for menu control. Hoang and Thomas developed an ultrasonic glove-based input device for distance based manipulation techniques [1].

Passive haptics have been employed in virtual and augmented environments to assist with realism and improve immersion [8]. A study by Viciano-Abad et al. [2] demonstrates that passive haptic feedback improves task performance with reduced errors. A table-mounted sheet of 'soft foam rubber' was used to support pointing gestures using fingers or with a stylus. The non-haptic condition had participants perform the task by stretching out their hands in mid-air. Kohli [9] explored a deployable substrate used with an AR system for a military training system. This system explored the idea of warping the augmented models so that the physical and virtual systems do not align exactly, and thus extends the deployable substrate to a range of virtual content. These passive haptic examples have not attached the soft materials directly to the user's body to enhance the interaction experience.

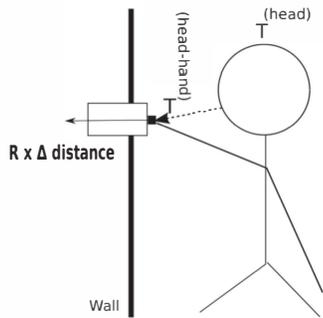


Figure 3. Transformation matrix of PDH technique. Delta Distance is controlled by the Passive Deformable Haptic glove to provide greater manipulation control



Figure 4. Door cut-out model added to the wall, with the user (artificially overlaid) performing the task.

Passive Deformable Haptic Glove Techniques

We present a set of interaction techniques enabled by the PDH glove to provide an additional 1DOF for depth information. Foam placement on the palm facilitates direct manipulation with tactile feedback and PDH support to reduce hand movements.

We utilize existing tracking techniques, whose mechanism is outlined in Figure 3, to determine the 6DOF pose of the glove. Combining the user's position transformation matrix, T_{head} , and relative position of the hand, $T_{\text{head-hand}}$, determines the location of the glove. The Digital Foam sensor provides tracking of Δ_{distance} . An additional orientation sensor can provide tracking of the rotation matrix R . We placed a fiducial marker on the glove to calculate the relative position of the glove to the user, using image plane technique.

Our three techniques (hole/trench cutting and chamfer) are designed to perform cutting and carving operations on existing models using a variety of cutter models such as cylinder, prism, or plane. The techniques operate with and without existing models. Extrusion can be performed by inverting the cutting operations.

Dwell activation

The PDH glove enables a natural and intuitive activation mechanism for modeless interaction. The user can start the operation by slightly depressing the Digital Foam sensor on the physical surface. The operation is committed using a dwell technique wherein the user maintains a constant deformation of the sensor for a period of time. The user aborts simply by removing their hand from the surface, thus resetting and cancelling the dwell time activation.

Hole Cutting

The PDH glove supports the task of cutting out a pre-defined shape to a certain depth on an existing object. The glove enables a modeless hole-cutting technique where the user simply walks up to the surface and starts to 'punch' the device at the desired location. The initial deformation of the foam will trigger the process. In addition to refining existing models, cutter models can also be created as stand-alone virtual objects in an unprepared outdoor AR environment. For example, the user can use the technique to create virtual doorways on a building site, as shown in Figure 4. An added orientation sensor to the PDH glove will enable different angles of cutting.

Chamfer

The user can manipulate virtual objects with a chamfer (also known as a bevel) operation by employing the PDH glove. This is achieved by pressing the foam against the corner edges of objects (see Figure 5 for resulting image). The deformation of the digital foam determines the depth of the chamfer. With an orientation sensor attached to the glove, the user can cut the chamfers at different angles and different functions (round, square). When there is a model of the physical object, the technique cuts directly onto the model. Without an existing virtual model, the chamfer technique will load the prism cutter model at the hand location, to change the appearances to look as if the edges have been chamfered away.

Trench Cutting

The user can move their hand across the physical surface to carve trenches into a virtually aligned surface. The user can create trench waves with different depths, with varying pressure, see Figure 7. A

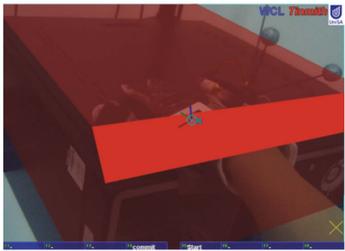


Figure 5. Chamfer technique is performed by directly touching the surface edges during manipulation

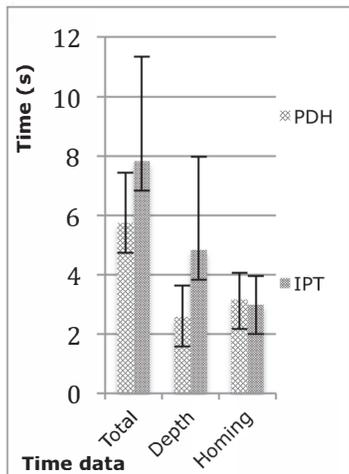


Figure 6. Mean (SD) time values for 2 techniques (in seconds)

practical example of this technique is a spinning clay wheel to mold various organic shapes. Variable depth trenches can be carved out to create complex shapes, with cutter objects of different shapes and sizes. Coupled with an orientation sensor mounted on the back of the glove, the user can carve different trench shapes by treading the hand in various angles on the surface to model organic shapes.



Figure 7. Trench cutting techniques on a solid surface

User Evaluation

We compared the PDH glove with an existing image plane technique, one of the common techniques for mobile AR systems, for undertaking a hole-cutting technique. Our hypotheses are: *The PDH glove improves task performance in terms of:*

- H1. *reduced overall completion and depth time.*
- H2. *reduced number of failed attempts.*
- H3. *reduced erroneous hand movement.*
- H4. *reduced fatigue.*

There were two independent variables: technique (PDH foam glove technique or existing image plane technique [7] (IPT)) and depth of task (5mm, 15mm, or 25mm). This is a 2x3 repeated measures design.

Design

The participant was required to complete hole-cutting tasks, with three steps: 1) positioning the virtual cylinder on the surface, 2) moving the cylinder down the required depth and 3) holding for two seconds (dwell time activation) to complete the task. We measured the time to complete step 1 as *homing time*, and step 2 as *depth time*, and the *total time* to complete the tasks.

The tasks were performed on a flat surface at torso height of a seated participant, see Figure 8. The three separate locations were located both close to the body and at arm full reach. Both PDH and IPT techniques employed the OptiTrack 6DOF tracking system on the surface, to remove the imprecise nature of the IPT technique. The end of step 1 was signaled by IPT technique with a keyboard press, to remove errors and speed considerations with novice users. In the second step, IPT condition employed the OptiTrack, by adjusting their hand position up and down in mid-air, and the PDH used the Digital Foam. Both conditions supported comparable sub-millimeter resolution tracking. Participants were required to hold the foam depression (for PDH condition) or their hand position in mid-air (for IPT condition) for two seconds within 2mm of the required depth to complete the task, referred to as *dwell time*. The dwell time was used to enable modeless interaction. In the IPT condition, the participant's hand is not supported by any means at any time. We collected the number of times the timer reset, when out of the depth range, as an indication of *failed attempts*. We captured hand location through OptiTrack and Digital Foam as erroneous hand movement, based on variance only in the vertical axis.

5mm	15mm	25mm
3.08 (2.68)	2.15 (2.49)	1.85 (2.16)

Table 1. Mean (SD) number of failed attempts across techniques

5mm	15mm	25mm
0.140 (0.0369)	0.130 (0.0402)	0.107 (0.0530)

Table 2. Mean (SD) of hand movement during the successful dwell time (mm), by OptiTrack and Digital Foam, across two techniques.

	PDH	IPT
During dwell time (OptiTrack & Digital Foam)	0.0977 (0.0313)	0.153 (0.0408)

Table 3. Mean (SD) of hand movement between 2 techniques (mm)

Participants completed a nine task block repeated two times for each of the conditions, randomized order with rest in between. The participants answered a questionnaire afterwards, regarding the level of fatigued felt, how easy and intuitive the techniques were to use and to reach the task's goal, and their perceived precision. Responses were recorded on a visual analogue scale.

Results

There were 20 participants (18 males, 2 females, mean age 25.55 years, SD 5.19) from the University of South Australia and the general public. We performed two-way repeated measures ANOVA over the factors of the hypotheses: *time (total, homing, depth), failed attempts, and mean erroneous hand movement during the last two second dwell time*. We performed the following analysis: between the two techniques, among the different depths level, and the interaction between technique and depth. The Mauchly's test for sphericity has not been violated. Table 4 outlines the mean and SD of the results data across all conditions (two techniques x three depths).

TIME

Figures 6 charts the results of time analysis. For total time, PDH technique was significantly faster $F(1,19)=8.90, p<0.01$. For homing time, there was no significant effect found across all the tests. The PDH technique has a significant effect of technique on depth time $F(1,19)=12.05, p<0.01$. Overall, *H1 was supported*. There was no significant effect of different depths nor a significant interaction between technique and depth.

ERRORS

The PDH had a significantly lower mean number of failed attempts of 1.37 (SD 1.14) than the IPT 3.34 (SD 3.03), $F(1,19)=10.56, p<0.01$. *H2 was supported*. There was a significant effect on depth of the task $F(2,38)=12.54, p<0.001$, see Table 1. Post-hoc analysis (with Tukey adjustments) showed a significant effect ($p<0.001$) between depths 5mm–15mm and 5mm–25mm only. Participants found the 5mm task to be more difficult with more restarts. There was a significant effect for interaction between the technique and depth $F(2,38)=4.87, p<0.05$.

HAND MOVEMENT DURING SUCCESSFUL DWELL TIME

The PDH (recorded by Digital Foam) has a significant advantage over IPT (by OptiTrack), $F(1,19)=46.44, p<0.001$, and depth $F(2,38)=50.71, p<0.01$, see Table 3, on mean hand movement during successful dwell time. *H3 was supported*. There was a significant effect on depth of the task $F(2,38)=50.71, p<0.01$, see Table 2. Post-hoc analysis (with Tukey adjustments) shows a significant effect ($p<0.001$) between all depth pairs. There was a significant interaction between technique and depth $F(2,38)=15.20, p<0.001$. The deepest task assists participants in steadying their hand.

QUESTIONNAIRE

A Wilcoxon signed-rank test showed a reported positive significant statistical effect for the PDH for: reduced arm fatigue, easy to reach the goal task, and precision on completing the task. *H4 was supported*.

Conclusion

We have presented the Passive Deformable Haptic glove with Digital Foam sensor to support precise direct touch manipulation modeling techniques. Our technique

	Mean (SD)
Total time (s)	6.79 (2.93)
Homing time (s)	3.09 (0.89)
Depth time (s)	3.70 (2.60)
Failed attempts	2.36 (2.48)
Hand movement during successful dwell time (OptiTrack & Digital Foam) (mm)	0.0126 (0.0458)

Table 4. Results across all techniques



Figure 8. Study set-up

allows arbitrary physical objects to be modified with virtual information through direct touch without prior knowledge of the physical geometry. The tactile feedback provided by the glove is demonstrated with interaction techniques (including hole/trench cutting and chamfer) with modeless activation and dwell time completion.

The results of our study showed that the PDH significantly improved the time to complete the task, decreased error rate, erroneous hand movement, and reduced fatigue. There was no significant difference between the PDH and IPT homing times. It is an indication that existing techniques can be used with the PDH glove with no reduced effect. There was no significant difference in task time between the depth levels. Therefore, our PDH glove techniques are applicable to all the range of depths supported by the Digital Foam sensor.

One limitation is the amount of pressure required to depress the foam may be too soft or too hard for some users. Changing the size and the density of the foam material for each user can help overcome this. The depth of the actual foam sensor also limits the range of manipulation distance. A thicker Digital Foam sensor with lower density can be used to increase the range of movement. We can apply a scaling factor to the mapping. There is a trade-off between range and resolution, depending on the requirements of the task.

In the future we would like to extend the sensor on our PDH glove to other parts of the user's hand, such as fingertips and the edge of the hand. We would like to explore the combination of multiple sensors for more complex interactions. We would also like to explore

other AR display technologies such as projectors in Spatial AR. Finally, we would like to explore combining our PDH sensor with our ultrasonic glove sensor, to provide a range of distance sensors to support the development of new interaction techniques.

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