TouchMover: Actuated 3D Touchscreen with Haptic Feedback

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ABSTRACT
This paper presents the design and development of a novel visual+haptic device that co-locates 3D stereo visualization, direct touch and touch force sensing with a robotically actuated display. Our actuated immersive 3D display, called *TouchMover*, is capable of providing 1D movement (up to 36cm) and force feedback (up to 230N) in a single dimension, perpendicular to the screen plane. In addition to describing the details of our design, we showcase how TouchMover allows the user to: 1) interact with 3D objects by pushing them on the screen with realistic force feedback, 2) touch and feel the contour of a 3D object, 3) explore and annotate volumetric medical images (e.g., MRI brain scans) and 4) experience different activation forces and stiffness when interacting with common 2D on-screen elements (e.g., buttons). We also contribute the results of an experiment which demonstrates the effectiveness of the haptic output of our device. Our results show that people are capable of disambiguating between 10 different 3D shapes with the same 2D footprint by touching alone and without any visual feedback (85% recognition rate, 12 participants).

Author Keywords
3D touchscreen, haptics, physics simulation, force feedback.

ACM Classification Keywords
H.5.2 [Information interfaces and presentation]: User Interfaces - Graphical user interfaces; Input devices and strategies

INTRODUCTION
The ability of modern computing devices to render high-fidelity and highly realistic visual and audio output far exceeds their ability to provide any meaningful haptic feedback. In fact, the only haptic feedback on today's computing devices that is in wide use is the vibro-tactile feedback built into mobile phones and game controllers.

While haptics research remains relevant and vibrant, existing solutions fall into one of the two common categories. They either have the haptic feedback mechanism co-located with the display, but are incapable of rendering large forces or displacement necessary for simulating resistance and collision with objects [3,12,15,23]. Alternatively, others can render medium forces, but those are perceived through an actuated proxy device (e.g., stylus, thimble) whose tip is sensed and actuated in up to three dimensions [10,11,21]. Such proxy-based solutions make it difficult to interact in a freehand manner typical of touchscreen interactions. The PHANToM's [21] maximum sustainable force is 6.4N, sufficient only for smaller forces (e.g., moving light objects). In contrast, TouchMover can produce up to 230N which is, to our knowledge, well beyond other haptic displays. E.g., a wooden block (1ft cube, 16kg), incurs 76N of static and 69N of dynamic friction force when being slid on a concrete floor (as measured) and TouchMover can easily simulate this.

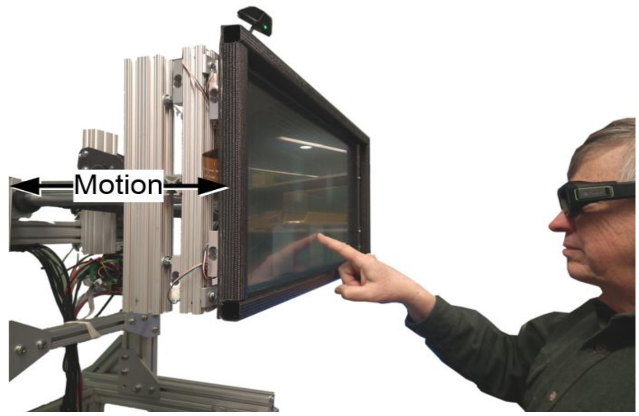

Figure 1. TouchMover co-locates immersive 3D stereo visualization, direct touch and touch force sensing with a robotically actuated display.

We describe a novel actuated display, called *TouchMover*, which is capable of generating large forces and displacements, as well as accurately co-locating the input and the output of both haptic and visual rendering (Figure 1). We combined 2D touch sensing, 3D stereoscopic visual rendering with correctly matched focus and vergence and a 1D haptic display within a single unit – a 3D interactive display with touch force feedback that is robotically actuated. TouchMover is fundamentally a 1D robotic arm moving in the Z-direction onto which we mounted a force-sensing 3D touchscreen. The user can touch and press on the screen to move it into a desired location and in turn, the screen can exert different forces onto the finger.

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This unique combination enables the user to maintain all the benefits of multi-touch touchscreens enhanced with the ability to move that screen in space and also simultaneously receive high-fidelity haptic feedback. It also has an added benefit when interacting with 3D stereo views: since our stereo convergence plane is set to be exactly at the screen depth, objects being touched are rendered with zero parallax (i.e., the depth of the screen plane, the fingertip, and the virtual object match exactly). Consequently, our design eliminates 3D touch selection problems [28] present when objects being selected are rendered with stereo parallax.

In particular, our work makes the following four contributions: 1) the design and implementation details of the TouchMover actuated display, 2) a solution for measurement of finger force separately from the force caused by the screen's inertia which enables correct force feedback while the screen is in motion; 3) four application prototypes which showcase different interaction scenarios with our device; and 4) experimental results showing that people are capable of disambiguating ten different 3D shapes on our device purely via touch-based haptic feedback and without any visual feedback. These contributions demonstrate the potential of TouchMover to deliver high-fidelity haptic and visual feedback and create novel immersive experiences.

Given its current size and power requirements, TouchMover is primarily a research tool; designed to help us and inspire others to explore scenarios combining touch, 3D vision, visual accommodation, and 1D haptics.

RELATED WORK

Providing tightly coupled haptic and visual feedback has been shown to improve the realism and immersion in virtual environments [6]. To our knowledge, TouchMover is the first solution which combines large force haptics, 3D stereo rendering and a freehand direct touch interface.

Haptics is an active research area and thorough review of related work is beyond the scope of this paper. For a more detailed (albeit dated) review of haptics (in connection with virtual reality) we refer the reader to [8,9]. We focus our review only on closely related work: 1) solutions that provide large force haptic feedback to the user's fingertip, 2) solutions which couple haptics and touchscreens, and 3) solutions which couple touch and 3D stereoscopic viewing.

A large portion of haptic research involves the use of impedance-type active haptic interfaces like SensAble's Phantom[1] and Novint's Falcon[2] plus a number of 2D+ cable-driven force feedback devices (e.g., [16,29]). Such haptic devices employ three or more actuators, orthogonally terminating at a single end effector point (usually a stylus tip). Kuchenbecker et al [18] installed a finger thimble at the end effector location of a Phantom device with fixed isolation compliance to engage the sensitive fingertip only when in contact with a virtual 3D surface. This was a haptics-only investigation with no visuals. Faeth et al. [11] combined a Phantom device with 3D geospatial data to provide a more intuitive interface for manipulating the data. Olsson et al. [22] studied the combination of graphics displayed on a half-silvered mirror with Phantom-based haptic feedback and concluded that, when the two are co-located, the spatial accuracy and object identification times were better. They also noted problems in spatial accuracy when there were conflicts such as haptic and visual registration depth cue mismatch. Large haptic forces are also achievable with worn devices (e.g., actuated gloves [7]), but such devices make it difficult to interact in a freehand manner typical of touchscreen interactions.

Several solutions attempted to integrate haptic feedback tightly with the touch display. Both [12] and [23] demonstrated small high-speed and low force actuators integrated directly behind the hand-held display. More recently, TeslaTouch [3] demonstrated how electro-vibration can be integrated with hand-held devices to change the perceived friction between the finger and the display. Both of these solutions allow for tight integration with the display, but are unable to provide larger forces or screen displacements. GyroTab [1] used the gyro effect in combination with a handheld touchscreen to provide reactive torque feedback, but the effects are less suitable for touch feedback and more for feedback relating the device movement. Hou et al. [16] used a thimble design plus programmable wire tension to effect lateral only forces and a torque on a finger when interacting with a 2D touchscreen with visuals. FingViewer [29] combines two such cable-driven actuators (one for each finger) and the touchscreen for creating in-plane haptic feedback to the user's fingertips as long as they use the cable connected thimbles. While they can provide complex in plane feedback (e.g., grasping feedback), their solution requires the use of thimbles and is unable to generate feedback coming from the display.

The closest to our design is the work by Hoshino et al. [15] who developed a Z-direction movable touch display for simulating force feedback for enhancing on-screen button activation. In contrast to TouchMover, their device was actuated via a pantograph mechanism, and was able to generate only small forces and short travel distances. TouchMover also provides co-located stereoscopic visualizations and enables the correct force feedback during the screen movement to create far richer user experiences, e.g., realistic force simulations with on-screen rigid bodies.

There are also a number of solutions which actuate or deform the display itself to provide haptic feedback. Examples include large pincushion-style displays [17], pneumatic displays [13], or actuated tiled displays [19]. While being more configurable and able to provide different feedback to

[1] http://www.sensable.com/haptic-phantom-desktop.htm

[2] http://www.novint.com/index.php/novintfalcon

different fingers, these systems depend on an external projector for display and have difficulties sensing direct touch. While not allowing for stereoscopic viewing or active haptic feedback, the Boom Chameleon project [26] is closely related to our efforts. There a touchscreen was mounted on a movable arm for both easy inspection and easy annotation of 3D objects.

There are relatively few technical designs that combine direct touch interaction with 3D stereoscopically rendered scenes and objects. Valkov et al. [28] built an elaborate projection screen setup to measure the disparity between location of a 3D stereo rendered object and the physical point of touch on the screen, given various positive and negative rendered parallax differences. They noted that if there as a parallax disparity, the users tended to touch between the two eye projections with an offset due to left- or right- eye dominance. Schoning et al. [25] described problems with parallax disparity between the direct touch and 3D object positions. They addressed solutions based on mobile devices.

Most of these applications and studies discuss and attempt to minimize touch problems due to the physical disparity between the 3D rendered object and the direct 2D touch surface position. We designed our device to overcome this problem directly since the touch surface is automatically moved to the object being touched as the user naturally approaches that object with their finger. This ensures that the finger, the rendering plane (screen) and the virtual object are on the same correct convergence plane, i.e. without parallax.

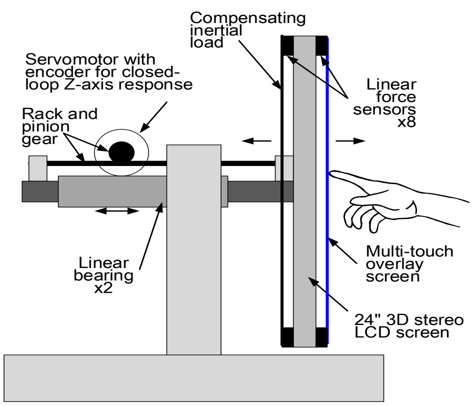

Figure 2. Simple diagram outlining major components of the TouchMover device.

DEVICE DESIGN AND IMPLEMENTATION

The original goal for this project was to use a robot-mounted 3D touchscreen monitor to explore how *the kinesthetic haptic sense* (i.e., the haptic sense relating to motion rather than tactile touch) can augment touchscreen interactions. To accomplish this we mounted a multi-touch stereo 3D monitor on a 1D robot. Our design was guided primarily by enabling the user to keep the screen within arm's reach in both extended/retracted arm position and to view it directly in the middle of the screen for viewing 3D visualizations head-on. We therefore opted for the standing height vertical screen, rather than having the off-axis perspective typical of horizontal displays. However, in principle, our design is capable of both vertical and horizontal operation.

3D Touch-Sensitive Display

We chose a BenQ XL2420T 120 Hz stereo 3D capable 24" monitor. We removed the plastic shell for weight reduction and to offer a more rigid mounting surface for other components. To the monitor frame we mounted four force transducers (Phidgets CZL635, 5 Kg load cells) on the front four corners. To these transducers, we mounted a lightweight polycarbonate frame with carbon fiber tubular stiffeners. The stiffeners were added to support the fragile thin glass touch overlay as it was designed to be mounted directly to a rigid LCD monitor. A 3M 98-0003-3775-2, 24" PCT multi-touch overlay glass with USB interface PCB was mounted to this stiffened frame. One advantage of our system over off-the-shelf solutions is that it allows us to combine touch sensing with a 3D stereo capable display, a combination not currently available on the market. Another advantage of this composite structure is that only the mass of the plastic frame and overlay touch glass were included in the touch force end effector and did not include the considerable mass of the LCD monitor, i.e., the force sensors were installed between the touchscreen overlay and the display itself (Figure 2). In our case, since the entire touchscreen part is moving, it is important to reduce the mass of the end effector since the force transducers sense not only the finger force, but also the acceleration of this mass as inertial forces. We will discuss this issue further below.

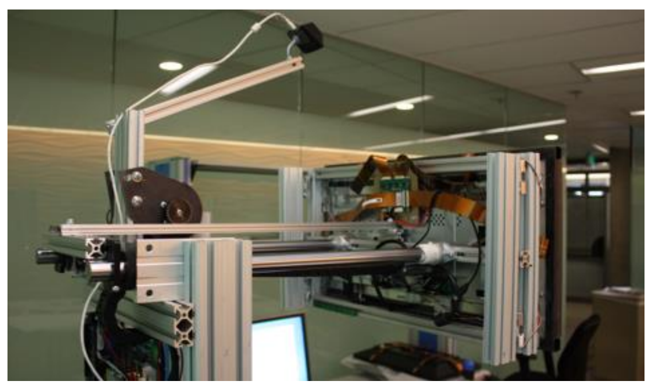

Figure 3. Image of the back side of our device showing the rack and pinion gear and the completely supported 3D touchscreen up front (consult Figure 2 for explanation of the components).

1D Robot Actuation

We implemented a 1D robot by combining an encoded linear actuator with two low friction (recirculating ball) linear bearings (Figure 2). The rotational output of an encoded gear head servo motor is converted to linear motion with a low-backlash rack and pinion gear. One end of the rack gear with its parallel linear bearings completely supported the display system (Figure 3). As a motion controller and driver we incorporated a Galil DMC-31012 single axis programmable servo controller with an integral high speed 32-bit processor, 16-bit ADC and 800 watt motor amplifier. The controller is capable of being programmed in a high-level interpretive language specifically for servo control.

The controller-amplifier communicated with a PC through a high speed Ethernet connection using communication interface provided by Galil[3]. The servo loop operated at 2 KHz within the controller and included processing the motor's encoder input, calculations for the system's position, integral and differential components (PID), servo motor updates, processing external forces sensed, communicating with the PC and processing for the numerous modes of operation. The full system schematic is depicted in Figure 4.

Most of the physical structure for the project was implemented using 80-20[4] modular framing. As the robot moved the display in a horizontally confined direction with the display being oriented vertically, the whole device was elevated such that the screen was situated at standard eye level for ease of interaction (screen center at 160 cm from the floor, our average user eye height). The small box suspended above the screen is the IRLED transmitter used to synchronize the stereo glasses (visible in Figure 1). The operable depth that our screen can traverse is 36cm.

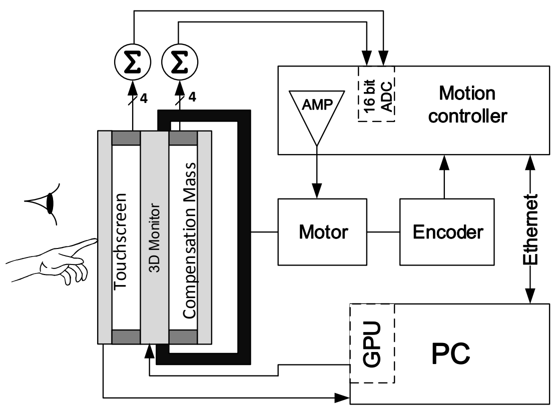

Figure 4. TouchMover system schematic.

For the computer, we employed a quad-core PC running Windows 8 with a GeForce GTX 660 Ti graphics card which gave us the ability to render video graphics in stereo using Nvidia's 3D Vision[5] output with their shutter glasses for stereoscopic 3D. The computer communicates with the motion controller via high speed Ethernet.

System Performance

To help the reader understand the capabilities of our device we now present the frequency (speed) and force response analysis of TouchMover. Figure 5 shows a Bode plot (frequency response) of our robotic system. We presented a linear frequency sweep as the input to the motion controller and recorded the screen's physical response. At low frequencies, the screen responds accurately to the commanded input of +/- 5 cm. At higher frequencies, the system cannot keep up and the amplitude drops below the commanded +/- 5cm. The half-amplitude drop off is around 8 Hz which is fairly fast for a system this large. Figure 6 shows TouchMover's force response. This shows that the screen's forcing ability fairly accurately corresponds to the commanded forces. We chose the force and displacement magnitudes that would be capable of simulating real-world examples such as moving items with varying coefficients of friction.

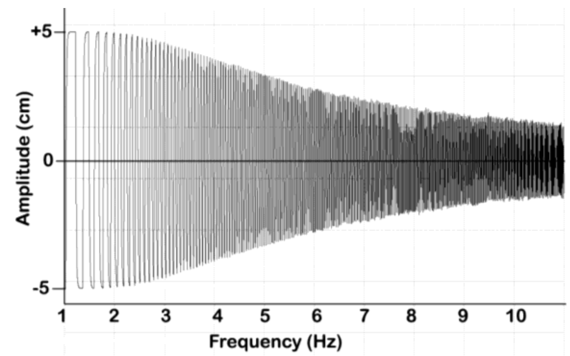

Figure 5. Bode plot of movement amplitude vs. frequency.

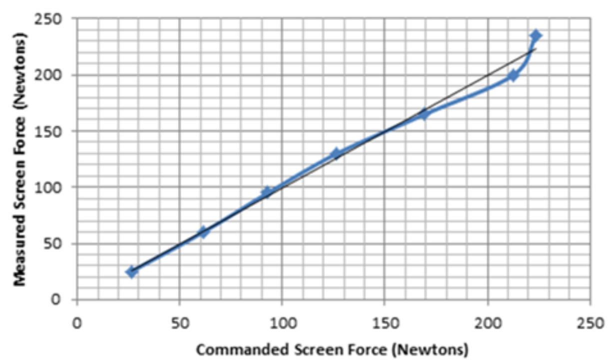

Figure 6. Plot of measured force vs. commanded force.

Simulating Haptic Sensations

When powered up, the controller causes the screen to extend all the way to find the Z=0 home switch and zero the encoder value when it finds it. The screen at this default position is fully extended toward the user. When the user touches the screen, they can push it into a desired Z position with a light pressure of their fingertip. This is the default behavior of our device which we refer to as the *idle* mode.

Since touchscreen interactions require the user's finger to remain in contact with the surface, the main challenge of the idle mode is to ensure that the screen remains in contact with the fingertip during interaction regardless of the direction that the fingertip is moving in (i.e., both away and towards

[3] http://www.galilmc.com/

[4] http://www.8020.net/

[5] http://www.nvidia.com/object/3d-vision-main.html

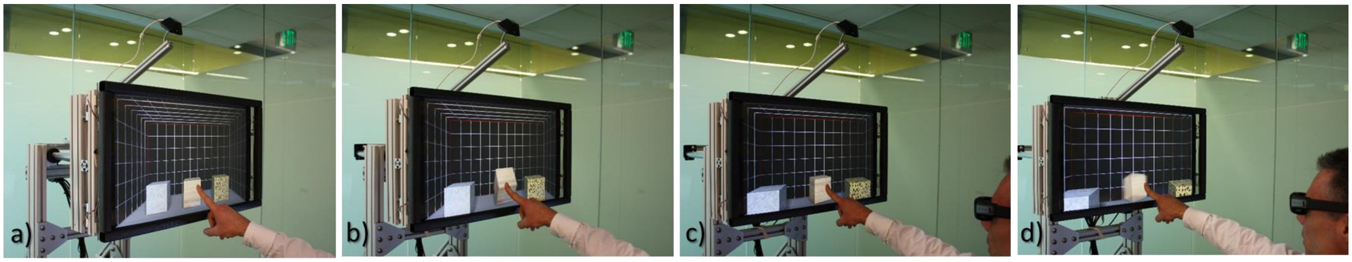

Figure 7. Application example of a 3D physical simulation with force feedback. By moving the screen with their finger, the user can interact with on-screen 3D objects and experience different force responses that correspond to the physical simulation. Note: stereo is absent from figure for clarity.

the user). To enable this behavior, we implemented an *idle force* with which the screen always pushes against the user. In the idle mode, the screen will start moving away from the user when the finger force exceeds the idle force of 15 Newtons (about the weight of a half of cup of water). With the maintenance of this small idle force, the screen follows the finger in depth excursions, both positive and negative, until a haptic force beyond the idle force is commanded such as when touching and interacting with an object.

In addition to *idle*, we implemented four additional command modes: *force*, *velocity*, *position*, and *detent*, where additional forces are added to the idle force depending on the XYZ position of the finger and the application requirements. For example, by specifying a fixed position command to the controller, one can direct the screen to remain exactly at a desired position, canceling the idle force. The detent mode adds a brief additional force to the output to create a haptic signal for the user (see detent description in the "Volumetric Data Exploration" section below).

Separation of Finger Force from Screen's Inertial Force

TouchMover's modes of operation require precise knowledge of the position and the velocity of the device itself and also the force impacted on it by the user's fingertip. Knowing this force is necessary to correctly enable the idle force behavior; however, measurement of the finger force alone is complicated by the movement of the touchscreen.

In particular, the summed analog output of the touchscreen mounted force transducers contains the force components due to finger touch plus inertial forces of the touchscreen during acceleration. This inertial component caused by the mass of the touchscreen (M_1) must be removed leaving only finger force. While theoretically one should be able to remove the inertial forces on the transducers by subtracting a correctly phased term (acceleration*M_1), in practice this depends on a very accurate estimate of the acceleration. In our initial implementation, this approach resulted in either an unstable actuation or a very sluggish response.

A more successful approach is to add another set of force transducers and an inertial mass (M_2) to the moving system, isolated from the touch force (see Figure 2 and Figure 4). This separate system senses only inertial forces from a compensating mass and not any force due to touch. This inertial-only force was digitally converted, scaled and subtracted from the converted touch-plus-inertial-force signal of the touchscreen. This enables us to correctly compute only the touch force. By measuring two forces (F_1 and F_2) our system can correctly isolate the force due to touch pressure (F_{touch}):

$$\begin{aligned} F_1 &= force\ signal\ from\ touchscreen\ sensors \\ &= F_{touch} + M_1 * acceleration \\ F_2 &= force\ signal\ from\ compensation\ mass\ sensors \\ &= M_2 * acceleration \end{aligned}$$

Thus

$$F_{touch} = F_1 - K * F_2$$

Where

$$K = M_1/M_2$$

This force separation is one of the contributions of our system. To facilitate this computation, we implemented two custom amplifier boards to boost and sum the microvolt signals from the strain gauge force transducers to a reasonable level for input to the 16-bit analog to digital converter (ADC) on the servo controller (Figure 4).

EXAMPLE APPLICATIONS

To illustrate the utility and versatility of TouchMover, we implemented four different application examples.

3D Physical Simulation with Force Feedback

Several previous research projects explored the use of touchscreens [27] and the space above the touchscreen [14] for creating physically realistic behaviors in a 3D scene. While visually realistic, such solutions offer no haptic feedback beyond the passive resistance of the screen itself. In contrast, our device is capable of producing human-scale forces against the user's fingers (ranging from 1.5N to 230N) as well as moving the touchscreen in space along the single axis.

We employed these capabilities to render realistic 3D physical simulations with both visual and haptic feedback. In particular, we implemented a 3D stereoscopic visualization which correctly moves the rendering plane according to the movement of the device itself. Also important was correctly rendering the scene from the observer's isometric viewpoint as the screen moved. While head-tracking would make this effect even stronger, for simplicity we set the user's viewpoint at a fixed distance from the screen (50cm).

Furthermore, our solution eliminates the disturbing 3D touch issues reported by Valkov et al. [28] where the users need to compensate for object parallax when touching stereoscopic objects on a fixed screen. When using TouchMover, the person's fingertip, the depth of the rendering plane, and the 3D virtual object that the user is "touching" all match correctly in depth.

In our application, the user is presented with three virtual 3D boxes, each with different virtual weights and respective friction forces, and the device simulates the appropriate force feedback when the user tries to push each box.

Placing the user's finger on the screen allows the user to gently push the screen in space until they encounter an obstacle (e.g., a box). To simulate physical behaviors we used Nvidia PhysX[6] physics engine and we represent the tip of the user's finger with an invisible sphere proxy particle (similar to the solutions in [14,27]). By applying a simulated force on the proxy particle corresponding to the actual force of the user's finger on the touchscreen display, we can correctly simulate the physical response that the virtual object should exhibit and also update the device's force response to the user accordingly.

While able to generate realistic responses, this application suffers from a fundamental limitation that only a single touch point can be handled in most cases. This is because the user interacts through one firm plane (the touchscreen) and therefore we are unable to exert different forces onto different touch contacts or sense different pressures from different fingers. In practice, this limits us to effectively using a single finger to interact with a 3D scene.

3D Contour Tracing

In addition to providing force feedback to the user, we can simulate a rigid 3D surface at different depths by physically moving the screen to the desired depth and locking it in place. By updating the depth of the screen according to the user's XY touch input on the screen we can simulate the surface contour of the 3D object as long as the object is contained within the working volume of the device. In contrast to the force feedback behavior, this mode of operation can be thought of as forcing the screen to a prescribed position.

To demonstrate this ability, we implemented a prototype application in which the system haptically renders the 3D contour of the touched object by moving the screen to the correct depth according to the user's finger XY position.

Figure 9 illustrates the user exploring the cup and the beach ball 3D objects. As with the force feedback example above, the user is restricted to a single finger.

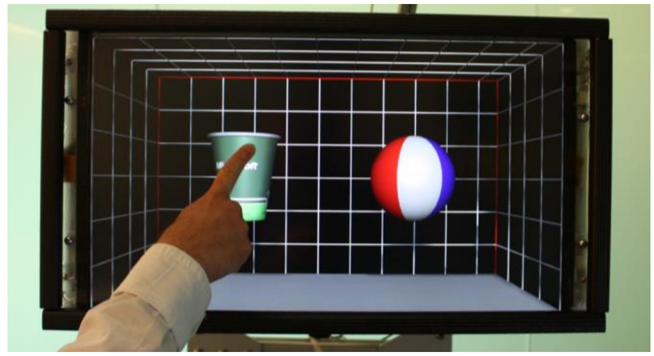

Figure 9. 3D contour tracing application where the user feels the shape of the 3D object by tracing their finger along its surface. Note: stereo rendering is disabled for clarity.

Volumetric Data Exploration

In contrast to the above applications which deal with 3D scenes, we now showcase using display movement and haptics to enhance interactions with 2D data. We implemented a volumetric medical image browser which shows the MRI scanned data of a human brain. By gently pushing on the screen the user can sweep the volume and view different image slices of the brain (Figure 8).

When the user is interested in further exploring a particular slice, they can touch an on-screen button with their non-pointing finger along the left or right side of the screen, and lock the screen position in place. This makes use of the multi-touch capability of the 2D touch screen. Now they can use their fingertip to annotate the slice while locking the screen into position with the other finger. To facilitate easier search and retrieval of such annotated slices, our device implements a haptic *detent* to mark that slice (inspired by Berdahl et al. [5]). In particular, whenever the user is navigating and returns to that slice, the screen braking force increases, causing it to stop at that slice. To continue navigating, the

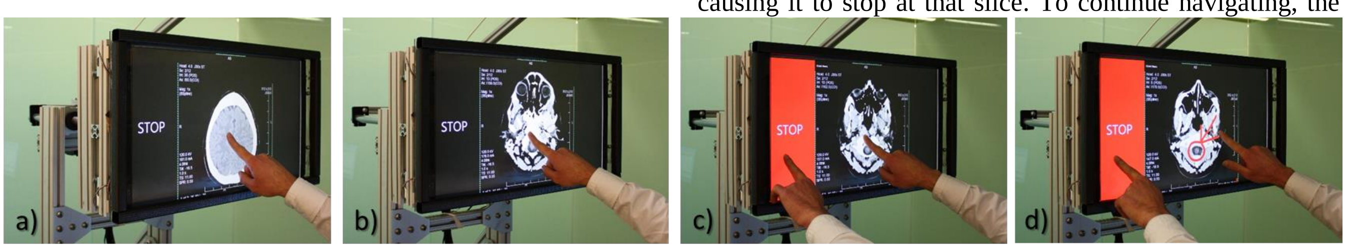

Figure 8. Interacting with medical volumetric data. We used the MRI scans of the human brain in our application. Pushing the display back reveals different images of the scan dataset (a-b). The user can prevent the device from moving by touching on a stop button (c) and then annotating the current slice with their finger (d).

[6] http://www.nvidia.com/physx

user must exert a finger touch force slightly higher than the idle force in order to move the screen past this slice and turn the braking force off. This detent makes it easier to find such information without resorting to an on-screen visual solution.

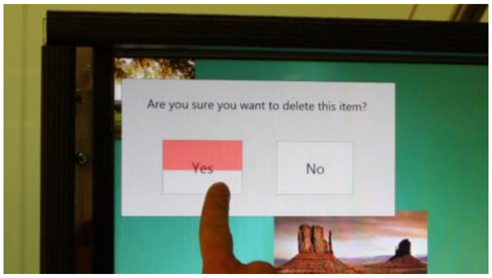

Figure 10. An example of touchscreen interactions augmented with kinematic haptics. Z-buttons (e.g., *Yes* confirming deletion) require higher force and larger displacement of the screen than others to eliminate accidental activation. The button rendering serves as a progress bar, visually reinforcing the amount of movement necessary to complete the action.

Haptic Button Activations

Lastly, we implemented a simple application which demonstrates using TouchMover's capabilities to reduce accidental activation of touchscreen buttons (similar to [15]). Users can be frustrated by accidental activations [4] and inadvertent activations can be costly (e.g., accidental confirmation to delete an item, illustrated in Figure 10). To reduce such errors, we prototyped *z-buttons* (inspired by Ramos et al. [24]) that activate based on screen movement rather than touch or force only. In particular, to activate such buttons the user must press the button and physically move the screen by a certain amount. To make z-buttons harder to activate accidentally, the system can apply more resistance, thus ensuring that the user's intentions are certain. While simplistic, this example showcases how even the simplest graphical user interface elements can benefit from the extra input dimension offered by our device.

EXPERIMENT

We designed our visual+haptic display to augment the on-screen multi-touch experience with co-located haptic sensations, albeit in 1D. In contrast to many existing touchscreen haptic solutions which exert minimal forces and are used mostly to render different surface textures or contact friction [3], our device is capable of exerting large human-scale force as well as rendering significant displacement in one dimension. This ability holds the potential to effectively render the actual 3D shape of the object that the user is touching on the screen. However, the effectiveness of this 1D haptic information channel is unclear, given that the user experiences it through the flat surface of the display which does not necessarily reflect the object's surface normal at the point of touch.

To evaluate the fidelity and effectiveness of our system in conveying the shape information through a 1D haptic channel, we designed an experiment where participants were asked to identify 3D shapes by touching them on the screen without any visual feedback. This task is similar to the haptic identification tasks suggested by Ballesteros and Heller [2]. While the stated goal of our overall system is to tightly integrate haptics with 3D rendering, evaluating the combined experience would be dominated by visual information. Therefore we focused our first experiment on validating the expressiveness of haptics alone.

The primary goal of our experiment is to demonstrate the expressive power of our device to render 3D geometry using a 1D haptic channel. If we can show that our device can convey the shape-defining characteristics to the user using only 1D haptics, then combining such haptics with co-located on-screen visuals should yield an even more convincing experience.

Setup and Procedure

We recruited 12 participants (6 male, 6 female, mean age 37.5, std. dev. 10.2) from the community. Participants received \$5 compensation and the experiment took approximately 30 minutes to complete.

The participants were asked to first familiarize themselves with the capabilities of our device by practicing with the 3D force feedback demos (Figure 7) and the 3D contour tracing

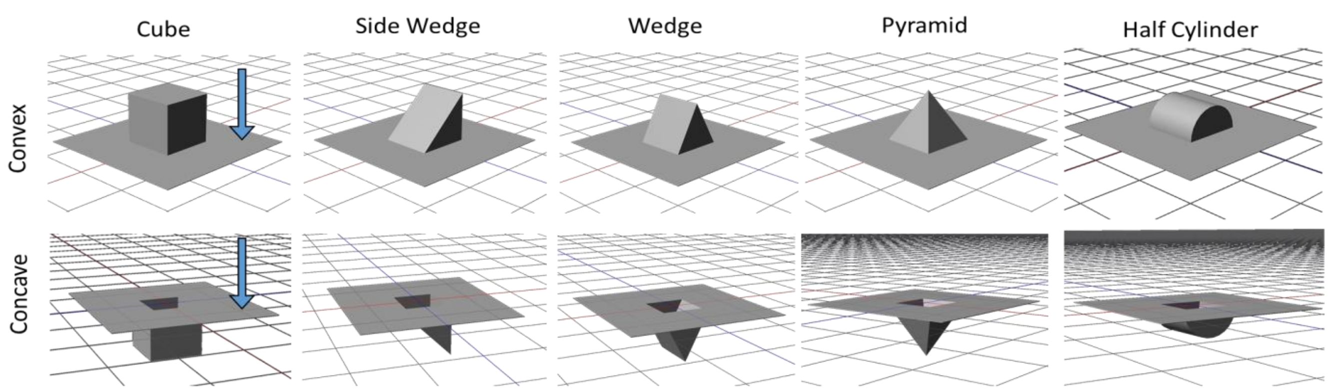

Figure 11. Ten 3D test shapes in our experiment. Participants were asked to recognize these shapes by touching them with a single finger without seeing any visual information on the screen. Note: the 3D shapes are shown from the side perspective for easier comprehension, but they were oriented vertically in the actual experiment; i.e., the plane supporting the objects above was parallel to the plane of our screen. The blue arrow shows the direction of the user's touch.

demo (Figure 9). They were asked to wear stereo shutter glasses, stand in front of the device, and use only the index finger of their dominant hand for all interaction with the device during the experiment.

To test participants' shape recognition performance, we created a set of five 3D geometries: cube, side wedge, wedge, pyramid, and half cylinder (Figure 11). All test shapes share the same footprint (15cm square), but differ in the overall 3D shape. Each shape was tested in both the convex (protruding) and concave (recessed) orientation, yielding 10 different 3D objects. We specifically chose shapes with the same footprint so that the user could not determine the shape of the object simply by the presence or absence of haptic feedback in the 2D plane of the screen.

Our test shapes were centered on the screen in the middle of the working volume of our device and haptically rendered by our system. The shapes were rendered in vertical orientation, either directly protruding towards the user (convex) or recessed away from them (concave). For example, the top of the pyramid was either the closest point towards the user (convex) or the furthest point away from them (concave). The participant only saw a white surface (Figure 12a) on the screen indicating where they can touch the shape. With the exception of this lack of visual feedback, the operation of the device was identical to the 3D contour tracing application.

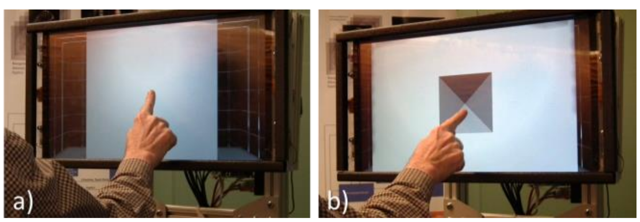

Figure 12. A participant in our study: a) during the trial without a graphical rendering of the shape, b) after the trial completed the shape was visually revealed. The shape in this trial was a concave pyramid.

After familiarizing themselves with the demos, the participants were given four practice trials to learn the task procedure. Practice trials consisted of shapes that were different from the shapes used in the actual test. Practice shapes had a circular footprint (cone and hemisphere) and were presented in both convex and concave form yielding the total of four practice runs. The cone shape used in our practice trials can be seen in Figure 15.

Participants were instructed to touch and explore the shape on the screen until they were confident that they could identify the shape of the object. Each participant was given the printed copy of Figure 11 as a list of choices, but was not told how many different shapes they would be required to identify or whether there will be any repeated shapes.

The trial ended when the participant verbally stated their guess for the shape they were touching. We recorded their guess as well as the time it took them to reach that guess. After each trial, we visually revealed the shape on the screen (Figure 12b) and the participant then had a chance to touch it again it if so desired. After verbally indicating that they were ready to proceed, the study coordinator presented the next hidden shape to the participant. Participants were presented with 10 trials (one for each condition) in random order.

Beyond our general hypothesis that the participants would be successful at identifying our test shapes (H1), we hypothesized that shapes that differ primarily in the gradient of their surface (e.g., wedge and half cylinder) will be the most confusing to identify correctly (H2).

Results

Confirming our main hypothesis, our participants were generally very successful in identifying the tested shapes. Participants indicated the correct shape 85% (+/- 4.3% SEM) of the time, taking 41.5 seconds to respond (+/- 8 sec SEM). Four out of 12 participants correctly identified all shapes (100% correct), and two participants with the lowest score recognized only 60% of the target shapes.

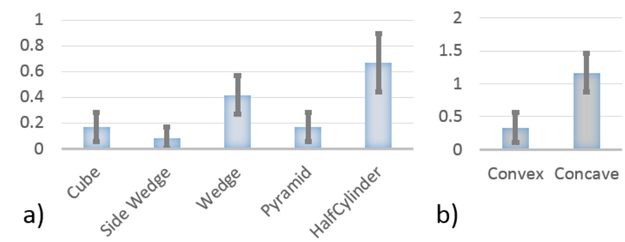

Figure 13. Average number of errors over 10 trials across all participants for a) different shapes and b) for shape orientation (convex vs. concave). Error bars show +/- SEM.

User Identified Shape

Tested Shape	Cube+	Cube-	Side Wedge+	Side Wedge-	Wedge+	Wedge-	Pyramid+	Pyramid-	Half Cylinder+	Half Cylinder-
Cube+	12									
Cube-		10						2		
Side Wedge+			12							
Side Wedge-				11		1				
Wedge+					11				1	
Wedge-						8				4
Pyramid+					1		11			
Pyramid-						1		11		
Half Cylinder+			1				1		10	
Half Cylinder-		2				2		2		6

Figure 14. Confusion matrix from our experiment showing the shapes that were most frequently confused by our participants. Convex shapes are marked + and concave - .

Participants were never confused between convex and concave shapes, i.e., participants never identified a convex shape as a concave or the opposite. However, identifying concave shapes resulted in more than three times as many errors than convex shapes (Figure 13b) (two sided t-test showed significance $p<0.01$). This difference was unexpected, since the concave shapes were simply the inverses of convex shapes. While our study does not offer us sufficient detail to understand the causes of this effect, we conclude that our device is better in haptically rendering convex objects than concave ones. We speculate that this might be due to the relative distance between the object and the user (convex objects reduced this distance) or that the user's finger is better in interpreting convex shapes when such are approximated with flat surfaces like our screen. However, at this point, the full understanding of this effect remains future work.

The half cylinder and the wedge were the most frequently misclassified shapes (Figure 13a), confirming our second hypothesis. Furthermore, the confusion matrix shown in Figure 14 clearly reveals that the concave wedge was misidentified as the concave half cylinder, while the concave half cylinder was confused for concave cube, wedge and pyramid. When asked about their difficulty in recognizing these shapes, participants frequently commented that it was difficult to differentiate the subtle difference in haptically rendered curvature of the half cylinder and the straight slope of the wedge.

We observed a significant learning effect between our practice trials (68% recognition rate) and the test trials (85% recognition rate), indicating that the participants got better with practice. We also observed a learning effect within our trials. When comparing the errors committed in the first five trials to the errors committed in the second (last) five trials we found a significant statistical difference for each participant: in the first half the average number of errors = 1.08, while in the second half the average number of errors = 0.45 (statistical significance confirmed by $p<0.05$ with two sided t-test). While this suggests that our participants would probably improve even further with more practice, we are encouraged that our participants achieved high recognition rates even with very few practice trials.

Overall, the study results confirm that TouchMover is capable of conveying significant amount of 3D shape information by the 1D haptic channel alone. Furthermore, in a post-session question and answer session with the participants, they all expressed confidence that they could use the haptic channel alone to identify simple shapes on our device.

DISCUSSION AND FUTURE WORK

In addition to our user experiment, we have demonstrated TouchMover to hundreds of people at a public demonstration event. While we gathered subjective feedback only, our demo users were impressed with the resolution, speed and capabilities of our device. We now summarize the feedback from our experiences in interacting with the device.

A problem we encountered early on was the friction between the user's fingertip and the touchscreen which made moving along the screen while maintaining contact difficult. We partially mitigated this effect by applying a clear lubricant to the touchscreen, significantly lowering the friction at the finger. Instead of this effective, but messy solution, we are considering reducing the surface friction in an electrostatic way (e.g., as suggested by [3]).

Though TouchMover is capable of rapid high-force and large deflections, the interacting fingertip is always touching a hard vertical plane of the screen. This makes discovering features such as sharp edges and textures difficult. For example, if the fingertip rests exactly on a sharp edge, the device might produce a large displacement with a minimal XY movement of the fingertip. This can be highly disturbing with large discontinuities in depth since the entire screen must move a large amount in a very short time. We currently prevent our device from exerting forces that could cause injuries.

Due to the rigid nature of our touchscreen, the force feedback is felt equally on all fingers in contact with the screen, which makes it impossible to provide the individual haptic feedback to multiple fingers simultaneously. While we focused our investigations on primarily single finger interactions, multi-touch interactions are plausible and implemented in our system (see "Volumetric Data Exploration"), but the haptic feedback is not completely correct in those instances.

While our preliminary experiment offered evidence of the effectiveness of the 1D haptic channel to convey shape information, more evaluations remain to be done. It is likely that more realistic tasks (e.g., with distracter objects) would make it more difficult to identify shapes. In addition, it also remains future work to evaluate the effectiveness of combined visuo-haptic experience, rather than haptics alone.

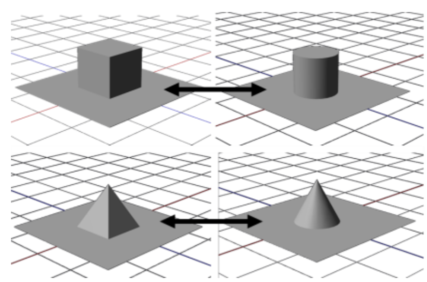

Figure 15. Examples of shapes that are difficult to disambiguate from only 1D haptic feedback in our system. Not being able to haptically render vertical edges (cube) or mostly vertical edges (pyramid) makes such objects confusable with similar shapes that don't have vertical edges (cylinder and cone respectively).

In addition, the single dimensional nature of the movement meant no variation in the surface normal could be explored. Vertically oriented edges are particularly difficult to recognize (Figure 15). Edges expressed in Z were difficult to ascertain as the absence of a correctly angled touch plane and/or lack of corresponding lateral forces masked expected haptic cues. Of course, rotating the shape in space to feel different edges of the object would make it possible to disambiguate such objects as the vertical edges would be haptically visible then, but this requires an additional step in recognition. The research of Zeng, et al. [30] offers a solution in the form of the tilting touch plane which remains an interesting avenue for future work.

Similar to prior research which combined haptic response and visual feedback [20] we observed that the latency and response from the PC was often not fast enough (120 Hz) to keep up with the controller for some of the modes of motion required. To combat that, we let the PC specify updates at the highest frequency available, but the controller handles the direct output of the device given PC instructions as a guideline. E.g., the controller can smooth out the output between two PC updates. Achieving higher PC throughput is an interesting area of future work.

Finally, there are a number of additional haptic stimuli we plan to explore, such as changing the compliance normal to an object's surface to simulate soft objects, and simulating various surface textures. The addition of small acoustic actuators to the suspended touchscreen could help increase the apparent frequency response of the system. While these will not result in large, high speed screen movements, they can add high frequencies to our high force, large deflection kinesthetic movements, thus imparting sensations such as texture and button clicks.

CONCLUSIONS

In this paper, we presented TouchMover, a novel visual+haptic device which combines 3D stereo visualizations, multi-touchscreen interactions, force sensing and 1D haptic actuation for a unique immersive experience. Our preliminary user study confirms that our device is capable of conveying enough information through the haptic channel alone for the user to be able to identify 10 different 3D shapes. Our example applications showcase how this functionality can be employed to greatly improve the existing touchscreen interactions with both 3D and 2D data.

While we understand that the size and complexity requirements of this system make it impractical for wide-spread use today, we believe that this device will serve as a research platform for better understanding of the value of the haptic sensations in touchscreen use.

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