TouchMover 2.0 -
3D Touchscreen with Force Feedback and Haptic Texture

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ABSTRACT

This paper presents the design and development of a novel visio-haptic device that co-locates 3D stereo visualization, direct touch, texture and touch force sensing with a robotically actuated display. Our actuated immersive 3D display, called *TouchMover 2.0*, is capable of providing 1D movement (up to 36cm), haptic screen force feedback (up to 230N) in a single dimension perpendicular to the screen plane, and has an additional capability to render haptic texture cues via vibrotactile actuators attached to the touchscreen. We describe the details of our design and improvements. We showcase how TouchMover 2.0 allows the user to: touch and feel the 3D contour and 2D texture of a topographic map, to interact with 3D objects by pushing them on the screen with realistic force feedback and intuitively explore and feel pseudo tissue texture within volumetric data from medical imagery (e.g., MRI brain scan).

Keywords: 3D touchscreen, haptics, texture, vibrotactile

Index Terms: Human-centered computing - Human computer interaction (HCI) – Interaction devices – Haptic devices

1   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 vibrotactile feedback built into mobile phones and game controllers.

TouchMover is an actuated display 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. We combine 2D touch sensing, 3D stereoscopic visual rendering with correctly matched focus and vergence and a 1D servo actuator within a single unit – a 3D interactive display with touch force feedback that is robotically actuated in the Z-direction (Figure 1). The user can touch and press on the screen to move it into a desired location and in turn, the screen can exert forces onto the finger.

Early in the development of TouchMover [8], it was obvious to the authors that the higher frequency haptic clues were missing.

Figure 1: TouchMover 2.0 co-locates immersive 3D stereo visualization, direct touch and touch force sensing with a robotically actuated display and a vibrotactile screen.

Specifically, the haptic response was limited to a relatively low frequency 1D actuation of the stereo touch screen. The user test of TouchMover consisted of requiring people to disambiguate ten different 3D shapes on our device purely via touch-based haptic feedback and without any visual feedback. These contributions demonstrated the potential of TouchMover to deliver high-fidelity haptic and visual feedback and create novel immersive experiences. Participants indicated the correct shape 85% of the time. User feedback however indicated the lack of edge definition or gradient haptics created problems with this task. Also it was noted that while the fidelity of the active visual and haptic interactive dimensions of this device was impressive, the lack of any texture haptics was apparent.

TouchMover 2.0 adds a Z-axis haptic texture to TouchMover via sub-audible actuators mounted to the touch screen. In TouchMover 2.0, the texture vibrotactile actuators respond to the XY position of the finger on the touchscreen in addition to the capabilities of the original device.

1.1   Related Work

There are relatively few technical designs that combine direct touch interaction with 3D stereoscopically rendered scenes and objects. Hoshino [4] et al. developed a movable screen in response to finger touch to enhance the actuation of virtual buttons. Their system had relatively short screen travel distance and no proportional force sensing.

Valkov et al. [7] 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 is 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. [5] 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.

Some researchers have been interested in exploring haptics without a screen. For example, Dostmohamed et al. [13] worked on a system known as "Morpheotron" to create a 3D surface in 2D by using the contact angle of a small plate under the finger. Their system didn't have the dimension of height. Later on, Wijntjes et al. [18] extended the "Morpheotron" to include height. Tachi et al. [14] explored displacement for displaying large shapes but they didn't represent the gradient of the shape. On the other hand Wijntjes et al. [15] researched curvature discrimination characteristics of human touch without displacement.

Various researchers explored shapes and textures on 2D displays. Saga et al. [16] developed a system which display shapes, textures, and visual images simultaneously by employing an illusional gradient sensation and recorded vibration. Kim et al. [17] also developed illusional-gradient-sensation-based electrostatic display. Bau et al. [20] used electrovibration to create tactile sensations. Projected deformable objects has been another field of exploration for researchers; For instance, Follmer and al. [19] worked on a shape display using an array of dynamic pins, depth sensor and an overhead projector.
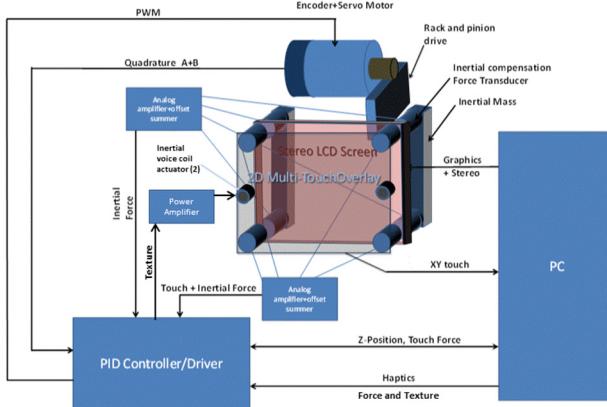
Figure 2: Simple diagram outlining major components of the TouchMover 2.0 device.

2 TOUCHMOVER 2.0 DESIGN AND IMPLEMENTATION

The 1D robot actuator of TouchMover [8] served mainly to apply the kinesthetic or proprioceptive haptic response that lets the user perceive the force, position and movement of their body. One deficiency of this system was the lack of the other important haptic sense – tactile or cutaneous perception that enables the user to explore an object's surface type with skin contact. Also, as the TouchMover 2.0's linear actuator operated into the upper frequency bands of its capability or above eight to ten Hz, the gear backlash of the rack and pinion system (mainly) became audible and distracting when exploring objects with these frequencies in their haptic pass-band. Choi and Kuchenbecker [2] create a good

overview of vibrotactile perception, displays, touchscreens and various actuators.

The goal for TouchMover 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.

2.1 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: The 1D Robot Actuation image of the back side of our device showing the rack and pinion gear and the completely supported 3D touchscreen up front.

As with TouchMover, we implemented a 1D robot by combining an encoded linear actuator with two low friction (recirculating ball) linear bearings (Figure 3). 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. 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 [9]. 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), servomotor updates, processing external forces sensed, outputting the vibrotactile signal, 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 [10] modular framing. As the robot moved the display in a horizontally confined direction (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 and was based on a normal interaction distance of a human arm.
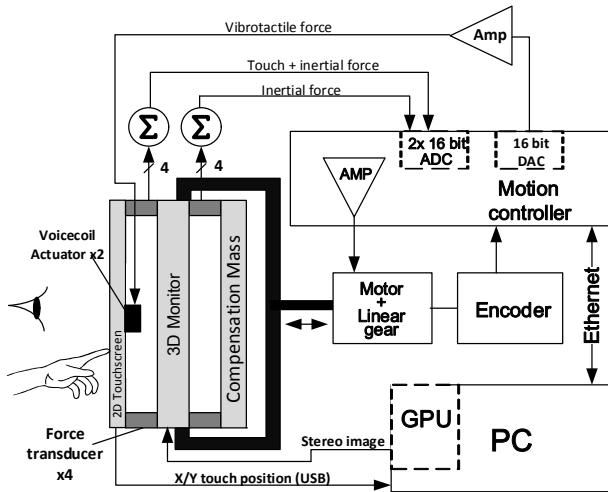
Figure 4: TouchMover 2.0 system schematic.

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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 [9] output with their shutter glasses for stereoscopic 3D. The computer communicates with the motion controller via high speed Ethernet.

To the kinesthetic only device, two vibrotactile intertial actuators, HiWave HIAX32C20-8, 30W Exciter, were added physically to the backside of the touchscreen overlay (Figure 5) to enable the screen to be physically vibrated along the Z-axis for higher frequency cutaneous haptics. An available 16 bit analog output of the Galil controller was amplified by a 50 watt, class-T audio amplifier, and fed to these tactile transducers in-phase. The 1D robot actuator signal was filtered to limit its output to below 8 Hz to help suppress the audio problem of the gearing. Since the PC update rate of the Galil controller was limited to around 60 Hz, the tactile transducers had their bandwidth limited to avoid aliasing artifacts imposed by the slow update of the PC communications. The upper end of the vibrotactile actuators' frequency response helped to convey higher frequency perception such as sharp edges of objects, even in the absence of real texture.
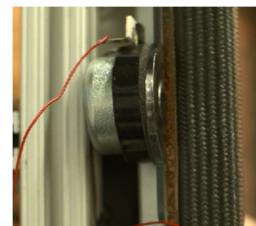
Figure 5: Vibrotactile actuator mounted to each side of the touchscreen.

2.2 System Performance

To help the reader understand the capabilities of our device we present the frequency response of both the kinesthetic 1D robot and vibrotactile actuators. We also present the force response analysis of TouchMover 2.0. Figure 6 shows a Bode plot (frequency response) of our combined robotic and vibrotactile system. We used a linear frequency sweep as the input to the motion controller and recorded the screen's physical response and recorded the real-time position as shown in Figure 6 (top). 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 and massive. Figure 6 (bottom) shows the system's response to the vibrotactile actuators alone. This was accomplished with a normalized swept sinusoidal frequency input to the actuators and measuring the screen's response by affixing a one axis accelerometer to the middle of the screen.
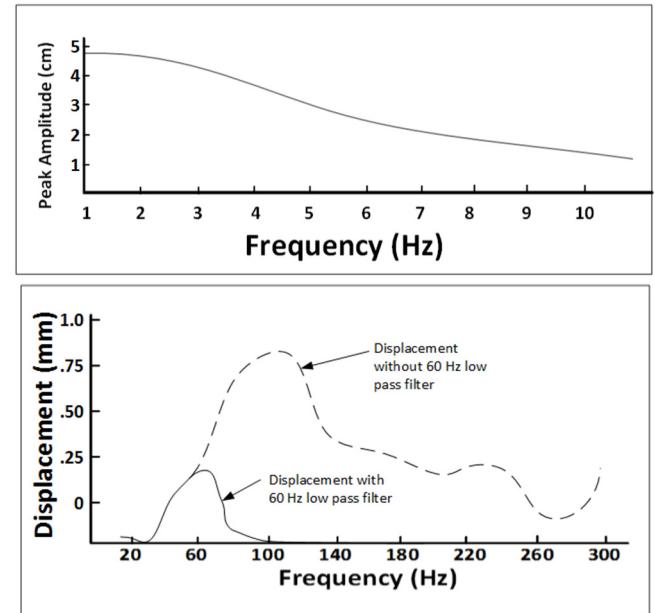
Figure 6: Bode plots of movement amplitude vs. frequency of the 1D Robot (top) and vibrotactile actuators (bottom).

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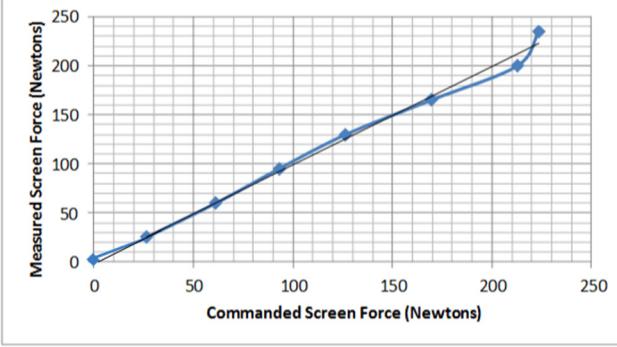
Figure 7: Plot of measured force vs. commanded force.

Though the frequency response goes well above 200Hz, the frequency was band limited to help suppress any audio perceived. It is difficult to suppress mechanical resonances as this plot indicates. The hump at 110 Hz was due to mechanical resonance.

Figure 7 shows TouchMover 2.0's force response. This implies that the screen's forcing ability closely corresponds to the commanded forces. We chose the force and displacement magnitudes that would be capable of simulating real-world kinesthetic examples such as moving items with varying coefficients of friction. Note the small finite force resulting from zero commanded force. This is the residual idle force. This research system was initially designed to be cable of replicating real-world forces without causing harm to the user which is the reason for such a high (capable) force of ~225N. This upper end of the simulation has not been used.

2.3 Simulating Haptic Sensations

When powered up, the controller causes the screen to slowly extend 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 (idle force) 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 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 0.6 Newtons. 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 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).

2.4 Separation of Finger Force from the Screen's Inertial Force

TouchMover 2.0'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.

We attempted deriving the inertial-only force data with a MEMS accelerometer but were unable to obtain the correct phase relationship with the touchscreen force for an unknown reason. A more successful approach was to add another duplicate 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 s 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}):

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

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).

3 EXAMPLE APPLICATIONS

To illustrate the utility and versatility of TouchMover 2.0, we implemented three different application examples: a 3D terrain map visualization, a physical simulation of friction, and a volumetric data exploration.

3.1 3D Terrain Visualization

Several previous research projects explored the use of touchscreens [6] and the space above the touchscreen [3] 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 shown in Figure 1 to render realistic 3D physical simulations with both visual and haptic feedback. We created a 3D terrain visualization demo to showcase all of the capabilities of our systems in a single application. By moving their finger on the screen, the user can feel the contour of the topographical terrain map (Figure 1). The 1D robotic screen linear actuators move the screen along the Z-axis to correctly represent the altitude of the underlying terrain (at the current XY location of the finger touching the terrain).

The vibrotactile actuators are used to render information about the terrain type (such as forest, water, rocks or grasslands). This information is rendered as high-frequency vibrations, simulating different surface textures. In this manner, the user can feel the difference between different terrain types even if they happen to be at the same altitude, i.e., it is possible to feel the difference between the ocean and the coastal land areas even as they both happen to be "at sea level".

Lastly, we render the topographical terrain map as a 3D stereoscopic visualization which gives the user wearing shutter glasses a correct perception of depth. Placing the user's finger on the screen allows the user to gently push the screen in space until they encounter the terrain. As the screen moves, we move the stereoscopic convergence plane with the interaction plane which ensures that the object the user is touching is always rendered without any parallax underneath their finger. Our solution eliminates the disturbing 3D touch issues reported by Valkov et al. [7] where the users need to compensate for object parallax when touching stereoscopic objects on a fixed screen. When using TouchMover 2.0, 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. The texture signal is sent only when the user's finger is actually in contact with the terrain.

3.2 3D Physical Simulation with Force Feedback

In another demo 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. While we previously presented this demo in [8], we are including here a brief description of it, as it clearly demonstrates the capabilities of TouchMover 2.0 to render static and dynamic friction forces while the display is in motion.

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 [12] physics engine and we represent the tip of the user's finger with an invisible sphere proxy particle (similar to the solutions in [3,6]. 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.

Similarly to the 3D terrain visualization, this demo uses stereoscopic rendering which gives the user correct depth perception and eliminates the parallax issues at the interaction plane. 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).

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. There were no vibrotactile haptics used in this example.

3.3 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 [7].

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 physically 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. [1]). 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 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.

In addition to the proprioceptive response pushing or pulling the screen to the desired slice, we implemented an image-derived texture manifested with the vibrotactile actuators. As the user explores the image with their finger, the grayscale under the finger is used to drive the vibrotactile actuators. Since this data was derived from an MRI device and not a scanning durometer, its feeling to the user does not replicate actually touching equivalent texture but does haptically communicate sensed boundaries used in MRI technology.

To help the reader visualize the vibrotactile response the user feels, we have included an oscilloscope trace in Figure 8. As this user moves his finger from the left end of the dotted arrow to the right side, the oscilloscope plots the real-time signal to the vibrotactile actuators. The scope trace is the actual grayscale value under the user's finger as it is slid across the screen. Since the inertial actuator's influence on the screen is only when it moves, the user feels the time derivative of this trace. While scrubbing the exploring finger over a tissue boundary such as the skull, the user feels the abrupt edge very noticeably and, in this case, in the correct direction.

4 DISCUSSION AND FUTURE WORK

Our previous study [8] showed that our system was able to effectively convey the contour of 3D objects, even without any visual feedback. The haptic texture displayed in TouchMover 2.0 appears promising to improve contour tracing experience. For example, the 3D terrain visualization example is a step toward being able to quickly feel an object and its texture and iterate before it is committed. We also see interesting opportunities in the medical field with the possibility of being totally immersed into an MRI scan which could be useful as a teaching tool, but might also help during a time critical surgery in the future.

Pseudo textures can also be explored. Buttons or extensions of same can be enhanced through real or postulated kinesthetic and tactile haptics. Button boundaries, click-dome forces, mechanical hysteresis behaviors and textures can be explored for better HCI on touchscreens

Figure 8: Interacting with a MRI scan dataset.

As a next step, we are planning to recreate our previous user study [8], but with TouchMover 2.0 to see if the addition of haptic texture channel is helping to better disambiguate the shapes that were often confused (i,e, between a wedge and a half-cylinder in the study) by rendering the edges of the shape with high-frequency texture. We are also interested in exploring more with the different types of haptic textures we can render with TouchMover 2.0 and possible improvement we can make to the hardware for a richer experience.

A logical extension to our present hardware would be impart some of the missing degrees of freedom. We plan to add a finger-size block, able to slide over the 2D touch screen, which are held in place and actuated by three or four thin tendons articulated by servo motors on the edges of the screen. This block, besides following the finger in its X, Y and Z, could impart two additional degrees of mechanical motion in Yaw and Pitch, reflecting the instantaneous surface normal of the object being touched. With these four newly added degrees of freedom – forces in X, Y, Yaw and Pitch - TouchMover3.0 would be able to kinesthetically impart five degrees of force to the finger for a much more realistic and compelling haptic experience.

5   CONCLUSION

In this paper, we have described the background, theory and design behind the TouchMover 2.0 project and the addition of vibrotactile actuators for tactile experience along with convincing applications. The TouchMover 2.0 platform demonstrates 3D immersive simulations with both high force kinesthetic and high-frequency tactile feedback co-located with an immersive stereo touchscreen. Kinesthetic force feedback combined with tactile or cutaneous forces enhance the haptic communication effectiveness of this device. The vibrotactile actuators on the screen go beyond many of the haptics rendered to large and small screens today. TouchMover 2.0's texture capabilities can be much less subtle than many of the offerings of today that are barely perceptible. We believe TouchMover 2.0 is a good foundation as a research tool for visio-haptic HCI.

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