ImpAct: Immersive Haptic Stylus to Enable Direct Touch and Manipulation for Surface Computing

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This article explores direct touch and manipulation techniques for surface computing environments using a specialized haptic force feedback stylus, called ImpAct, which can dynamically change its effective length and equipped with sensors to calculate its orientation in world coordinates. When a user pushes it against a touch screen, the physical stylus shrinks and a rendered projection of the stylus is drawn inside the screen, giving the illusion that it is submerged in the display device. Once the users can see the stylus immersed in the digital world below the screen, he or she can manipulate and interact with the virtual objects with active haptic sensations. In this article, ImpAct's functionality, design, and prototype applications are described in detail with relevance to the concept of direct touch, giving special attention to novel interaction scenarios and design challenges. Furthermore, a technical evaluation was done to study ImpAct's accuracy and controlability and the results presented. This article concludes by discussing ImpAct's current limitations and future perspectives as a direct touch and manipulation tool.

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1. INTRODUCTION

Taking a step forward from traditional screen displays, touch and multitouch-based computer platforms, particularly surface computing, has become the modern trend. The commercial success of mobile multitouch devices such as the iPhone (Apple Inc.) and Android (Google Inc.), and developments of FTIR-based multitouch technologies [Han 2005] are promising signs for future dominance. However, touch surfaces pose several limitations in the context of touch, such as limited interactions with 2D surfaces and the lack of physical feedback [Wang and Ren 2009]. Simply put, in surface computing, users touch the surface of the screen, not the digital world behind it.

Direct touch is the way we touch and manipulate objects in the real world, in which geometric coordinates of the visual system and the haptic system are perfectly superimposed on each other. In other words, sources of both visual and haptic information are spatially coincident. Though it is the natural way, many haptic display systems tend to follow an indirect touch approach [Minsky et al. 1990; Kyung and Lee 2008; Lee et al. 2004]. This is especially true for haptic systems that are based on kinesthetic sensation, and are commonly used for object manipulation tasks [Kamuro et al. 2009; Massie 1996]. Our approach is to bring the direct touch techniques to the surface or screen display-based computing platforms.

This article explores direct touch and manipulation techniques for surface computing environments by using a specialized haptic force feedback stylus called ImpAct (Immersive Haptic Augmentation for Direct Touch). The proposed haptic stylus is a pen-shaped device which can change its length when it is pushed against a display surface. Along with the length change, a virtual stylus is rendered inside the display device, causing the user to believe that the stylus penetrated the display surface and entered the shallow region below the screen. Once the user can see the stylus immersed in the digital world below the screen, he or she can manipulate and interact with the virtual objects displayed in the digital world, as he or she uses a stick to manipulate objects at the bottom of a pond (illustrated in Figure 1). The user's hand feels the haptic sensations of the virtual touch via a force feedback mechanism built into the physical stylus. Hence ImpAct provides an interface that spatially joins haptic and visual information with multiple degrees of freedom, thus we call it a direct touch interface. In contrast to existing interface techniques, direct touch and manipulation provides a broader interaction space and novel design possibilities. The proposed system can be used to improve the user's experience of existing surface computing environments, and gives rise to novel application and interactive techniques. We propose ImpAct as a HCI (Human Computer Interaction) tool to enable direct touch on existing surface computing platforms.

2. RELATED WORK

The concept underlying ImpAct combines two fields of research into a single stream: surface computing and haptic interfaces. These two fields take

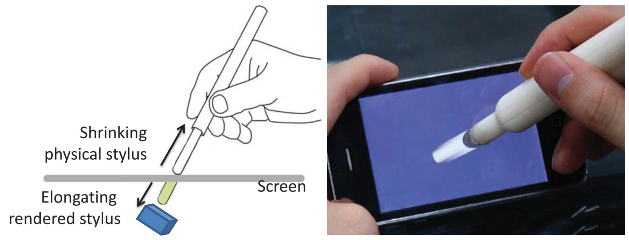

Fig. 1. Operating principle of ImpAct. When a user pushes ImpAct against the screen, the physical stylus shrinks and the virtual elongates (left). Users watch as ImpAct penetrates the screen and is immersed in the digital space (right).

mutually exclusive approaches to implementing rich user interfaces, and also, efforts are being made to combine them into a single interface strategy.

There are many approaches to extend the interaction space of surface computers beyond the 2D plane. An early one was to sense the degree of touch as a z axis control [Lee et al. 1985; Sinclair 1997; Ramos et al. 2004]. However, the detectable range of pressure variation is very limited and has a poor controllability at high resolutions. Direct z axis control has been implemented by Lapides et al. as 3D Tractus using a moving display, but the display can move in only one direction, and no rotations are allowed [Lapides et al. 2006]. Furthermore, size, shape, and directionality of the touched area on the surface was taken as an independent variable for input commands [So et al. 1999; Rekimoto 2002; Wang et al. 2009]. This can enable various interaction scenarios for surface computing such as virtual force metaphor, rotation metaphor, and so on, as presented by So et al. [So et al. 1999].

Wilson et al. proposed a technique to detect user hand movements above the display surface area in order to bring the planar gestures of surface computing into a three-dimensional gesture space [Wilson et al. 2008]. The BiDi screen is another, similar, gesture manipulation system [Hirsch et al. 2009]. However, these systems provide no feedback to users' hands and no visual contact between manipulated object and touch point. This could lead to ambiguity and confusion in object selection and manipulation.

Many assistive technologies such as stylus, mouse, and so on, are used in order to improve the interaction capabilities of surface computing systems. Suzuki et al. proposed a set of enhancements to a stylus by tracking user actions performed in air using an accelerometer [Suzuki et al. 2007]. Furthermore, Bi et al. explored the possibility of using pen-rolling as an input method for pen-based interactions [Bi et al. 2008]; Tian et al. presented the concept of a tilt menu to further explore stylus-based interactions [Tian et al. 2008]. Using tilt and rolling as direct cues for interaction could be very useful; however, since normal styluses are completely external to the touch surface, input and function could result in a lesser correlation. ImpAct does not use orientation and rolling as stand-alone interaction cues, rather they are used to calculate its projection inside the screen. Possible other assistive technologies are presented in the Bricks project [Fitzmaurice et al. 1995] and soft-touch interfaces [Sato et al. 2009].

Haptic interfaces emerged into the general HCI field from early development stages of modern computers [Minsky 1995; Ando et al. 2002; Massie 1996]. Massie proposed the PHANTOM, a point force-feedback display system for HCI purposes [Massie 1996]. The difference between PHANTOM and ImpAct is that ImpAct follows a direct touch approach, while PHANTOM was originally designed for indirect touch. The haptic pen [Lee et al. 2004] and the wUbi-Pen [Kyung and Lee 2008] are successful haptic stylus implementations with tactile sensation. However, both represent 2D surface details as cutaneous sensations, and does not have any means of enabling direct touch. Pen de touch is a much more advanced haptic stylus, which can give partial kinesthetic sensation to the fingers [Kamuro et al. 2009]. However, it is meant to be used above the display surface and does not provide direct touch features.

Most of the reviewed techniques still sustain the boundary between the real world and the digital world on the surface of touch. Others bring the interaction above the screen, disrupting the visual continuity of touch and the display system. ImpAct enables direct touch on surface computing environments, and the interaction possibilities proposed are nontrivial compared to existing technologies.

3. DIRECT TOUCH

The concept of direct touch introduced in this article is driven by two main guidelines: (1) that visual and haptic information should spatially coincide; and (2) multidimensional interaction should be enabled within the digital space.

ImpAct implements the first direct touch guideline via the illusion of permeability, created using simulated projection rendering (SPR). SPR produces a visual illusion to the user in which ImpAct penetrates the screen surface and goes through to the digital space below. The haptic information derived from the interaction within the digital space is conveyed to the user's hand via the stem of the stylus, so that the user perceives it as originating from the visual location of the interaction.

Latest research has shown that there are perceptual links between haptic and visual sensory events which are spatially coincident. Specifically, cognitive systems perceive visual and haptic sensory information as a single unit when their source is spatially coincident [Driver and Spence 1998]. Furthermore, static and dynamic links between visual and haptic perception were confirmed by Gray and Tan [2002] and Kennett et al. [2001]. Hence the first direct touch guideline can improve human perception of virtual 3D environments.

Multiple degrees of interaction, enabled by the direct touch concept, increase the user's capability in expressing complex 3D information to a computer. The 6DoF interaction space created by ImpAct conforms to this requirement. Existing interfaces for 3D environments use regular geometric shapes such as spheres, pyramids, and so on, as input units to create 3D graphics. Using direct touch tools, a user can express 3D data in irregular forms using multiple DoF interactions. This improves the user's expressive level of "tacit knowledge" [Polanyi 1959] to a computer.

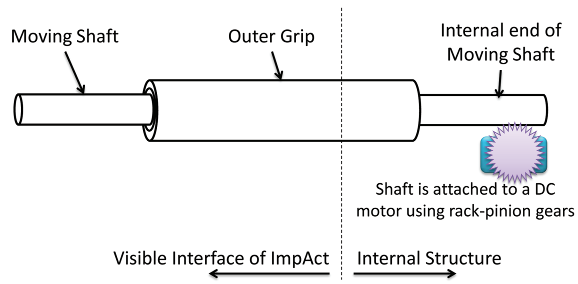

Fig. 2. ImpAct consists of two cocentric cylindrical shafts, one hollow and the other solid, so that the solid shaft can move inside the outer grip. The back-end of the moving shaft is attached to a DC motor to provide haptic feedback to the user.

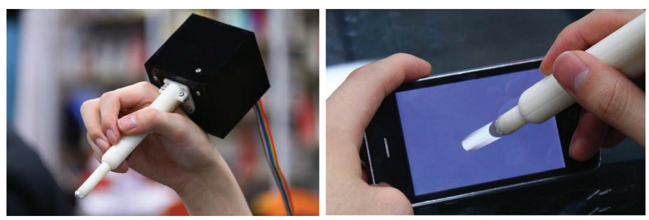

Fig. 3. ImpAct prototype. *Left*: a user holding ImpAct in his hand; *right*: view of the combined effects of the change in physical length along with the virtual stylus, resulting in the effect of penetrating the digital space.

4. IMPACT

As briefly introduced earlier, ImpAct is a special stylus designed to enable direct touch for touch screen-based display devices. ImpAct's stem is created using two cocentric cylindrical shafts, one hollow (like a tube) and the other solid, so that the solid shaft can move linearly inside the outer tube (grip). The user grips ImpAct's outer tube so that the inner shaft can move within the outer tube. The relative movements of the shaft and tube make the physical stylus change its length. The back-end of the moving shaft is internally attached to a direct current (DC) motor via a rack-pinion type transmission mechanism. This configuration is shown in Figure 2.

The DC motor can restrict the movement of the inner shaft, and can forcibly move the inner shaft through the gear mechanism. This can be utilized to implement a force-feedback haptic interface. For example, if the tip of the ImpAct virtual stylus hits a rigid wall inside the screen (i.e., a digital object), applying a restriction to the moving shaft will stop the user from pushing it further down the screen. Furthermore, if there is a moving object, ImpAct can simulate the effect of motion against the tip of ImpAct by forcibly elongating or contracting the length (i.e., moving the inner shaft in either direction). Figure 3 shows the prototype of ImpAct on a user's hand and the illusion that the display surface is being penetrated and is entering the digital space using simulated projection rendering.

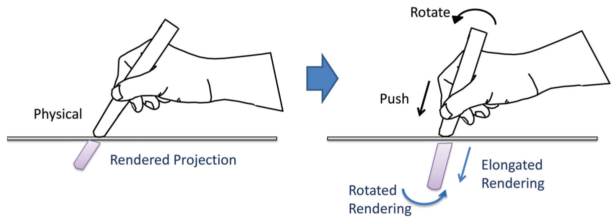

Fig. 4. Operating principle of simulated projection rendering. *Left*: virtual stylus is rendered along the physical stylus to make a visually continuous interface; *right*: rendered stylus is matched to all of ImpAct's dynamics.

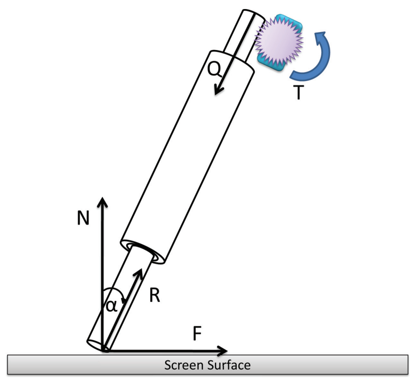

Fig. 5. Force-feedback using the screen surface as grounding.

5. DESIGN AND IMPLEMENTATION

This section discusses the design considerations and implementation approach of ImpAct.

5.1 Simulated Projection Rendering

Simulated Projection Rendering (SPR) is one of ImpAct's core concepts that drives its direct touch features. When users push the ImpAct against the screen, the physical stylus will shrink, while a projection will be drawn inside the screen, continuously mapping ImpAct's angular and length changes to that of the projection, causing it to align visually with the physical stylus. This process is called *simulated projection rendering*; that is, projection is simulated according to the dynamics of the physical stylus, thus its name.

5.2 Force Feedback

Figure 5 shows the mechanism used by ImpAct to exert force on a user's hands. The motor attached to the moving shaft can exert a torque τ, and the moving shaft conveys the force Q along the axis of the shaft to the display surface. This force creates two reactive forces on ImpAct's touch point and surface: normal force (N) and friction force (F). According to Newton's laws, the two forces N and F should create a resultant force R that is equal to the initial force Q in

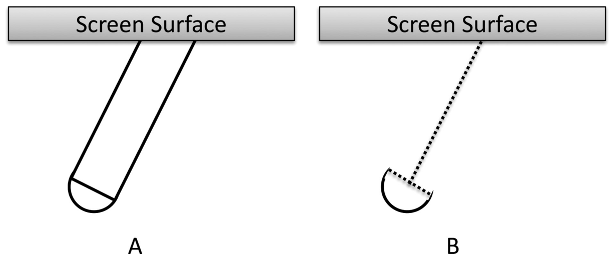

Fig. 6. Haptic and visual models of ImpAct. (A) the visual model and (B) the haptic model.

magnitude and opposite in direction. The user feels the resultant force R as a force-feedback.

5.3 Virtual Haptic Model

It is important to create a haptic model that can simulate plausible haptic cues for a user's hand by utilizing ImpAct's capabilities. ImpAct's haptic model described in this article is governed by the following basic rules.

(1) Only the forces with a nonzero component directed along the axis of actuation (axis of the cylindrical shaft) of ImpAct are simulated.
(2) The friction components and torques are neglected.
(3) Forces are simulated only if they interfere with the tip of ImpAct 's virtual stylus.

Rule 1 is derived because ImpAct is not capable of interpreting forces that are perpendicular to ImpAct's actuation axis. Rule 2 discards the friction components to eliminate complex calculations. Previous research shows that many meaningful haptic interactions involve little or no torque [Massie 1996]. (The effects of the second rule are further described in Section 8.1). Furthermore, object interferences on the cylindrical component of the virtual stylus are neglected, and only the tip is considered a haptic-sensitive area. This differentiates the visual and the haptic models of the ImpAct's virtual stylus. This is shown in the Figure 6, where (A) shows the visual model that is rendered inside the screen and (B) shows the model used to calculate forces from haptic interactions.

Three different kinds of force-exerting surfaces are analyzed to create haptic stimulations. Other complex shapes are not implemented in the current design. Figure 7 shows the three shapes being considered for implementation in the current prototype. They are (A) force exerted by a spherical object; (B) force generated by a plane surface; and (C) force generated by an edge.

5.4 Implementation

ImpAct has both sensing and actuation built into it. Individual functions can be listed as follows:

(1) measuring ImpAct's change in length;
(2) measuring orientation (yaw, pitch, and roll);

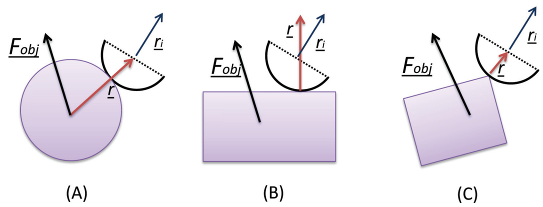

Fig. 7. Calculating the forces for haptic interaction. Force exerted by a spherical object (A), a plane surface (B), and an edge (C).

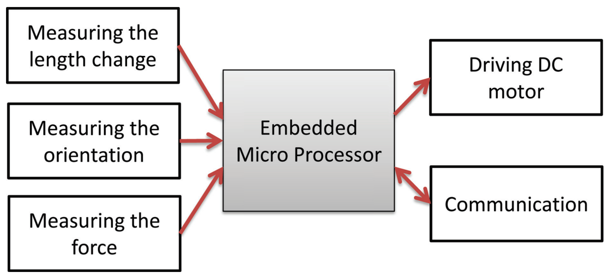

Fig. 8. Functional block diagrams of the internal electronics.

(3) measuring the force exerted by ImpAct on the user;
(4) driving the DC motor to control the force exerted; and
(5) communicating with the surface computing system.

ImpAct consists of a collection of electrical sensors and actuators along with an embedded microprocessor to control their functions. Figure 8 demonstrates individual functional blocks of the internal electronics and their controlling authority of the micro processor.

ImpAct's span length is measured using a linear potentiometer with a pressure-sensitive actuation. The potentiometer has an active length of 5cm with 10kOhm resistance. Position measurements are done at a rate of 10kHz. Orientation is measured using a combined accelerometer and magnetometer-sensing device (mounting is shown in Figure 9). We use a Honeywell HMC6343-type sensor for orientation-sensing, which gives 10Hz update rate at a 0.1° resolution of angular measurements in 10bits-long data words for each angle.

The actuation force of the shaft is generated using the torque τ generated by the DC motor. Torque is directly proportional to the current flow to the motor. Hence measurement of current flow can be taken as an indication of the force being exerted. We use the Honeywell's CSLW Series miniature, open-loop current sensor to measure the current flow into the motor. Frequency of measurement is 10kHz at a 8bit resolution. The DC motor is controlled by the embedded processor using the pulse width modulation (PWM)-based DC motor driver (5kHz), intersil HIP4020. The motor is the HS-GM21 SD, small-form factor motor with max loading torque 300gcm with gears. Its average current rating is 65mA and loading current is 200mA. Figure 9 shows

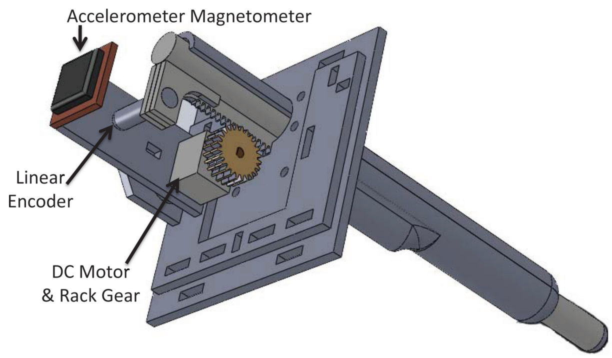

Fig. 9. Structure of the electronics components in ImpAct.

Table I. ImpAct's Hardware Specifications

Specification	Unit	Value
Weight	Kg	0.243
Ram Span (Min)	mm	3
Ram Span (Max)	mm	50
Voltage	V	5.0
Current (Idle)	mA	50
Current (Max)	mA	250
Residual Friction	N	3.58
Max. Force	N	10.8

the internal structure and layout of some of the visible components inside ImpAct.

Communication with the surface computing platform is done via the RS232 serial communication protocol. ImpAct uses a baud rate of 38400 per second to communicate with the computer. In the current prototype, ImpAct uses an external power supply due to space limitations. However, it can be powered by an integrated battery because of its low power consumption (max 250mA, average 60mA (active), 5mA(idle), 5V).

5.5 Physical Specifications

Specifications are listed in the Table 1.

5.6 Software Implementation

We developed two software interfaces for ImpAct: one is for the iPhone (3G 8GB) and the other is for a tablet PC (SlateDT, Inter Core Duo 1.8Ghz, 1GB, WIndows XP). Both applications use the OpenGL library for graphics. The iPhone application is written in the Objective-C language and the tablet PC version uses visual C^{++} and Java 3D. The software system is responsible for two basic functions: one is to render the 3D visualization according to the sensor data acquired from ImpAct and the touch point on the surface; the other is to transmit the haptic information such as a collision to ImpAct.

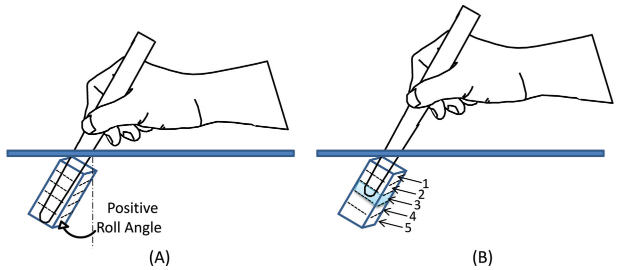

Fig. 10. (A) Orientation test; (B) z axis control test.

6. TECHNICAL EVALUATION

Prior to the user study, we evaluated ImpAct's device errors without user intervention. The combined errors existing in the system are calculated by analyzing raw sensor measurements of the device while it is kept in a steady rest position. We placed ImpAct on top of a table in a stable position and collected the data for a 10s time interval. We calculated the errors of yaw, pitch, roll, and span-length measurements compared to the mode of the dataset. This error value indicates the relative stability of the overall system measurements. Yaw, pitch, roll, and span-length measurements had average errors of 0.07°,0.00°,0.05°, and 0.00cm (respectively, SD 0.51, 0.11, 0.43, and 0.00). So we can assume that the combined system stability is good enough compared to the absolute errors of individual sensors.

We then conducted a user study to evaluate ImpAct's accuracy and operability. In the study, we examined the accuracy of orientation measurements and span length (z axis controllability) of ImpAct when a user is asked to achieve a given orientation and depth on the visual display. In the user study, a software-equipped tablet PC was placed on a table and users were given chairs to sit on. Additionally, since the projected graphics can be changed according to the perspective angle, a head rests were given to user so that all of them look into the display from the same position. We evaluated the system with 13 (3 female) volunteer participants with a mean age of 29.5 (min 22, max 47) years. All the participants were college students (with no relationship to the project) and everyday computer users.

We conducted two tests with each user: (1) calculated ImpAct's orientation errors; (2) calculated ImpAct's z axis control errors. As shown in Figure 10, a visual guide was shown to the user on the screen, and, in the first test, users were asked to align ImpAct's virtual stylus with the orientation of the guide. Without loss of generality, we only conducted the angular accuracy for roll angles. (But we are hoping to conduct a proper study for pitch angle in future.) The guide was placed according to randomly selected roll values between $\pm 30^\circ$ with steps of 5° excluding the angle 0°. In this test, 40 iterations were carried out per user. At each iteration, the user's alignment angles, guide angles, and the time to complete were recorded. A total of 520 iterations were recorded for all 13 users.

In the second test, users were given a 3D slider with a highlighted block, as shown in Figure 10(B), and asked to locate the end of the rendered stylus within the highlighted area. The test was conducted with 4, 6, 8, and 10 levels per slider, and a highlighted block was selected at random. Per each level, one user carried out 10 tests, summing to 40 iterations per user and 520 iterations for all 13 users. At each iteration, the difference from the tip of the projected stylus to the middle of the highlighted area was recorded as the radial error in controlling the span length.

Average completion time for each iteration for the first test was 4.9 seconds and the average absolute error (absolute angular error from the guide roll to the ImpAct roll) was 5.6° with a standard deviation of 6.2. Compared to the full span of the roll angle, the error was 3.1%. We believe this error is within the acceptable range for general applications.

Contributing factors to this error are the control dificulties due to the bulkiness and weight of the prototype and accuracy in measuring the accelerometer.

Average completion time for the second test was 4.46 seconds. We found that the average error of the span length to the actual highlighted area of the given guide was 1.47cm with 0.75 standard deviation. This is a 29.7% error compared to the full span of ImpAct, 5cm. We also noted that 98% of the time, the error made was negative. This means that in most of the cases, users pushed beyond the required target length. The error rate was significantly high, and should be reduced for proper operation. We observe that the contributing factor for this error was due to ImpAct's residual friction. We address these issues in our next prototype by changing ImpAct's transmission mechanism.

7. INTERACTION SCENARIOS

This section introduces selected applications, which can describe ImpAct's interaction capabilities in terms of manipulation, probing, and free-form creation. We describe them along with example prototype applications.

7.1 Manipulation

Manipulation involves understanding the object geometry, applying force, and motor control with multisensory feedback. In a computer-generated 3D environment, manipulation requires sequential input to specify the amount of movement, direction, and force (if physics is implemented). In contrast, ImpAct can act as a tool, where users can directly manipulate objects with combined visual and haptic feedback. It would be analogous to using a carving tool, paint brush, or a screw driver.

We use a billiard game to demonstrate ImpAct's manipulation capabilities. In existing CG billiard games, users have to instruct the power level using a slider like a GUI controller and give the angles separately. In the proposed application, ImpAct can be used as the billiard cue. Therefore, playing is superfluous, since all the parameters are calculated using ImpAct's orientation and the speed with which the user hits the cue ball, exactly similar to how one would play it in real life (additionally, ImpAct gives the haptic sensation of an impact). Figure 11 shows an image of a user playing billiards using ImpAct.

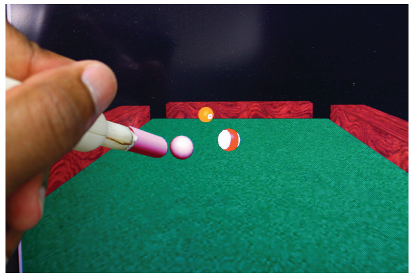

Fig. 11. Using ImpAct to play a billiards game.

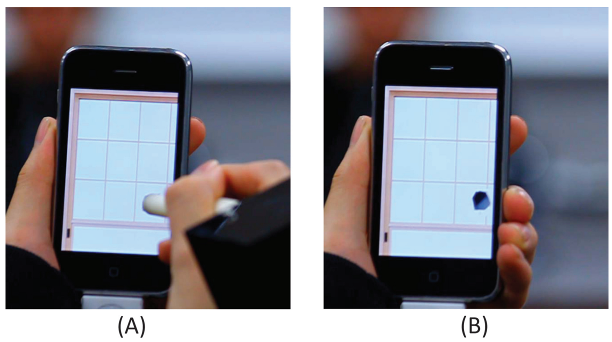

Fig. 12. Using ImpAct to play Shouji.

7.2 Probing

ImpAct can be used directly to probe a CG object inside a computer and to understand its physics such as resistance to move- strength or the dynamic forces it creates. In this section we present two probing applications, the first one is to demonstrate the simulation of static force, and the second to demonstrate dynamic force using ImpAct.

7.2.1 *Shouj.* Shouji was developed on iPhone as a mobile game, where a user can tear a computer-generated Japanese- style paper window to see through to the other side. As shown in the Figure 12(A), a user can push ImpAct against the paper window to break it. At first, the user will feel the stiffness of paper, but once the force reaches the breaking point, the user will feel the impulse and ImpAct will go through the paper window. After breaking, the user can see to the other side of the window via the video captured by the iPhone camera, as shown in Figure 12(B).

7.2.2 *Heart Beat.* In Heart Beat, by pointing ImpAct's tip near the heart of a virtual animal shown in the screen, the user can feel the heart beat of that animal. Figure 13 shows an image of a frog's heartbeat being probed. (In addition to the frog, this application can demonstrate human and horse heartbeats.)

Fig. 13. Probing the heart beat of a frog.

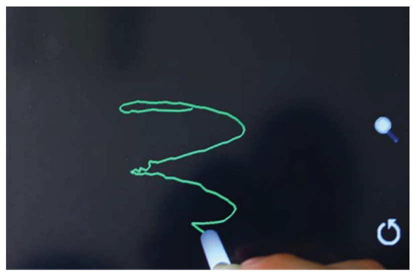

Fig. 14. Free-form drawing with ImpAct.

7.3 Free-form Creation

For many existing 3D drawing or modeling tools, users have to provide sequential inputs to define 3D objects and relations, since input devices are limited to 2D. But with ImpAct, users can access the 3D space directly by using XY translations along the touch surface and Z axis control using the span length. This capability enables ImpAct to make a free-form creation environment for 3D modeling.

We developed a simple 3D drawing application to demonstrate this feature. In general, if a user draws with a generic input device, he or she has to change each dimension to create 3D sketches. However, in the free-form application, a user can utilize ImpAct's z axis movement to create 3D drawings directly. Figure 14 shows an image of a 3D drawing using this application.

Another possible application of ImpAct is to create textures and drawings on irregular 3D surfaces. ImpAct's force-feedback mechanism can manipulate a user's hand so that he or she can draw or create texture on the surface as drawing on a physical, irregular wall using a paint brush. Figure 15 illustrates this application, which we call haptic-assisted drawing.

8. DISCUSSION

The concept of direct touch is a theoretical approach to develop a mechanism to create an ideal visual and haptic interface. In this article we discuss how to design and implement such a tool. However, conversion from theory to practice presents a number of design challenges which can and cannot be addressed by using the current prototype.

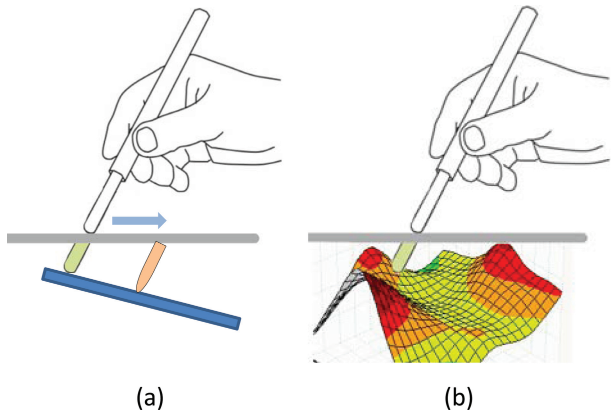

Fig. 15. Haptic-assisted drawing.

8.1 Design Challenges

We have identified some design challenges to the concept of ImpAct from the perspective of direct touch and human computer interaction in general. The first challenge is that the user's reach into the depth of the virtual world is limited by ImpAct's maximum spanning length. One possible solution is to attach a scaling factor to the virtual stylus so that the elongation is multiplied by this factor compared to the change in physical length. Another important limitation of ImpAct is that it is unable to provide the sensation of force that attracts a user's hands to the screen. ImpAct's force-feedback only works for the forces emitted from the surface and not towards the surface. Furthermore, as introduced in Section 5.3, ImpAct neglects the simulation of torque. However, in the process of creating haptic forces by using the screen surface as grounding, there is a possibility that the user will feel unnecessary torque sensations. As a solution, ImpAct should create a reverse torque to cancel such residual effects.

8.2 Limitations and Future Work

In this section we identify some existing limitations in the ImpAct prototype and possible solutions to overcome them. The most obvious and significant limitation of ImpAct is the bulkiness of the prototype and its weight. It greatly reduces ImpAct's operability. We are planning to implement the scaled-down version of ImpAct by moving the processing components and some of the electronics to an external box. The other limitation is the residual friction that exists in the ram. It causes low span length controllability in ImpAct and creates an undesirable force in haptic display. This friction component is made by the gear mechanism used in the motor and the wiper actuator used to actuate the potentiometer. We are planning to reduce this by utilizing a better transmission system in the next version. Another limitation in the current prototype is the existence of visual misaliganments in perspective in the rendered projection due to the unavailability of head tracking. Since we have not implemented head tracking, the rendered projection of ImpAct could not align exactly with the physical one; however, we are in the process of implementing head tracking for ImpAct.

9. CONCLUSION

In this article we presented the concept of direct touch and manipulation techniques for surface computing environments and introduced ImpAct as a tool and a proof of concept for implementing direct touch. Direct touch is meant to provide a spatially coincident haptic and visual display system along with free-form interactions within a given digital space. In the future, ImpAct could be used as a physical tool for modeling, texturing, and manipulating in CAD/CAM applications, new gear for gaming, a probing tool for medical field, and so on. As we have shown, using ImpAct makes it possible to implement direct touch, may enable a number of nontrivial interactions, and creates a clear path forward for potential future applications.

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