Proceedings of the ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC/CIE 2012
August 12-15, 2012, Chicago, IL, USA

DETC2012-71326

ACTIVE-HAND: AUTOMATIC CONFIGURABLE TACTILE INTERACTION IN VIRTUAL ENVIRONMENT

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ABSTRACT

We present a novel, low-power and untethered pneumatic haptic device, namely the ACTIVE-Hand, for realistic and real-time 3D gaming experience. Currently, body-motion based 3D gaming systems primarily use visual feedback to provide partly immersive gaming experiences. Tactile feedback systems in Virtual Reality provide immersion with high tactile resolution, but they are expensive and difficult to setup and calibrate. The conceptually economical modular design of the ACTIVE-Hand allows easily configurable tactile feedback as per application requirements. Contrary to commercial systems like Wii™ which provide global vibrations as a proxy for synthetic tactile feedback, the ACTIVE Hand is comparably lightweight, yet scalable to meet localized tactile resolution requirements. The ACTIVE-Hand provides controllable pulses for dynamic virtual interactions such as pressing virtual buttons and hitting moving virtual balls. We successfully demonstrate the paradigm of dynamic tactile interactions in virtual environments through a 3D Pong game by integrating the ACTIVE-Hand with Kinect™ camera.

NOMENCLATURE

P_i,V_i Pressure,Volume of air inside a closed pneumatic system at neutral state.
d Distance of the piston away from neutral state.
$P(d)$,$V(d)$ Equilibrium pressure inside a closed pneumatic system when the piston is at position d.
A Cross section area of the piston.
x,y,z Coordinates of the user in the virtual environment. x direction represents distance from left to right, y direction represents the height, and z direction represents the depth into the screen.

INTRODUCTION

In recent years, motion based 3D gaming has gained record-setting popularity with the commercial success of the Nintendo® Wii™, Sony® PlayStation™ Move, and Microsoft® Kinect™. With these systems, the user's body motion is captured in real time by either accelerometers or optical sensors and interpreted for intuitive control of the video games. Current motion based gaming primarily uses visual and audio feedback to provide partly immersive gaming experiences. Although the users are using their bodies as the controller, their experience is incomplete if they cannot touch and feel the virtual environment. Imagine playing a virtual basketball game on a TV and being able to touch and feel the ball. Imagine navigating through a virtual room while being able to feel the handle to the door. Nintendo® Wii™ and PlayStation™ Move use global vibration as a proxy for tactile feedback to engage users, but it is inadequate in producing localized tactile feedback people commonly experience in real life.

Haptic systems in virtual reality provide high tactile reso-

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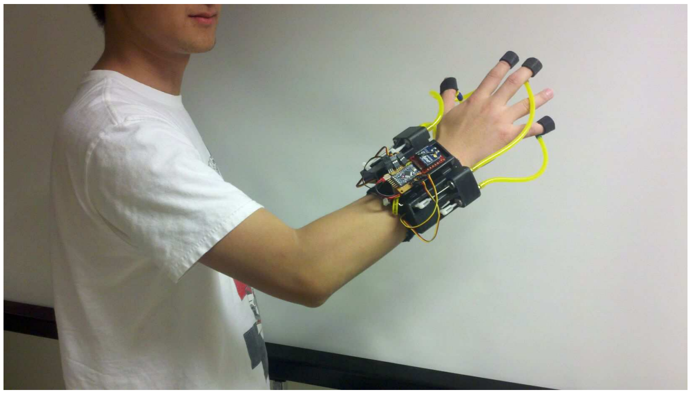


FIGURE 1. A user wearing the ACTIVE-Hand.

lution and realistic interaction. Haptic devices are commonly divided into two categories, desktop devices and wearable devices. Desktop mounted devices, such as the SensAble® PHANToM™ [1], provide force feedback [2] that can resist the user's motion and simulate the realism of contact [3]. Compared to desktop haptic devices, wearable haptic devices provide tactile feedback [2] while allowing the user a relatively large working volume [4] and dexterous manipulations of virtual objects [5] [6]. These are all desired in motion based 3D gaming experience.

Several problems with current haptic devices in virtual reality hinder their implementation in motion based 3D gaming. In order to integrate with motion based 3D gaming, the haptic device must be ungrounded, giving the user freedom to move. Desktop haptic devices do not meet this criterion. Commercially available wearable haptic devices such as Cybergrasp™have minimal constraints on the user's motion, but they cost thousands of dollars. Other wearable haptic devices such as the Gravity Grabber [7] provide tactile feedback to each fingertip, but their weight on fingertips can result in fatigue and negatively influence the user's touch perception [8]. There should be minimal weight on the user's hand, and pneumatic haptic gloves solve the problem. However, pneumatic haptic gloves [5] [6] are usually tethered to remote pressurized air sources resulting in constraints on the user's freedom of motion.

We present the ACTIVE-Hand, a novel, lightweight, low-power and untethered pneumatic haptic feedback device that provides localized tactile feedback to discrete locations. It overcomes many of the problems described previously. A prototype of the ACTIVE-Hand is demonstrated to provide tactile feedback to four fingers per hand. Nonetheless, the modular design of the ACTIVE-Hand allows easily reconfigurable tactile resolution as per application requirements.

We also introduce a new paradigm of gaming experience named Automatic Configurable Tactile Interaction in Virtual Environment (ACTIVE) by integrating the ACTIVE-Hand with a depth camera, such as the Microsoft® Kinect™sensor. In this paradigm, users can perceive localized tactile feedback simultaneously with dynamic virtual interactions such as pressing virtual buttons and hitting moving virtual balls. The tactile feedback is presented in the form of controllable pulses. In addition, the ACTIVE system is economical and easy to setup. This paradigm of ACTIVE is successfully demonstrated through a "3D Pong game". In the rest of the paper, the Microsoft® Kinect™sensor is denoted as Kinect for convenience.

RELATED WORK AND OUR CONTRIBUTION

Untethered Pneumatic Glove

Numerous work has been conducted on the development of pneumatic haptic gloves. Direct-drive actuator pneumatic actuators [5] and pneumatic muscles [6] have been used to simulate grasping force. Balloon actuator arrays [9] are used to generate tactile feedback in a compact and high speed manner. Although these pneumatic gloves are worn on hand, they are tethered to their grounded auxiliary units, e.g. an external pressurized air source. Even when pneumatic gloves become untethered [10], system complexity makes them unnecessarily cumbersome.

The ACTIVE-hand was designed as a simple and completely untethered haptic feedback device. The key design feature is a lightweight closed-loop pneumatic system. The ACTIVE-Hand does not require external air source; rather, it runs on battery to power actuators which drive the pneumatic system.

Dynamic Tactile Interaction

In the ACTIVE paradigm, tactile feedback was correlated with interactions with dynamic objects in the virtual environment, such as hitting a moving virtual ball. In order to easily detect users' motion, Kinect is selected to be the sensor. To the best of our knowledge, there has been only one publication that integrates wearable haptic devices with Kinect. SIRSLab in University of Siena, Italy [11] developed a hand tracking algorithm to utilize 3D data from Kinect for haptic rendering when interacting with quasi static virtual objects. However, hand tracking is just the first half of a successful haptic rendering. In our system, we assume that the hand is being tracked in a robust manner. Thus, we focus on the investigation of force variations associated with dynamic object interactions in conjunction with developing a wearable haptic device. When a dynamic object impacts a person's hand, it is important calculate and mimic the force variations in order to give a realistic touch feeling.

ANALYSIS OF TOUCH

In real life, people are frequently engaged in transient events such as pressing a button and hitting a ball. In these activities, the tactile information is presented as pulses which varies within a range of frequency and magnitude. Impulse-based tac-

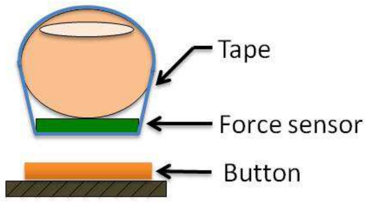
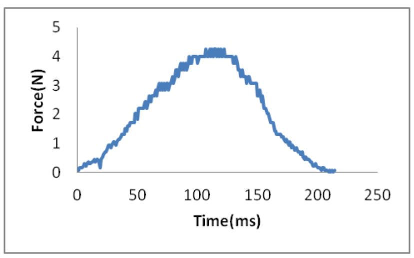
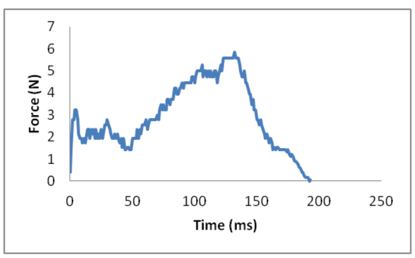


FIGURE 2. Illustration of the experiment conducted to measure the reaction force on the palm side of the index fingertip when a person pressed on a soft button.



(a)



(b)

FIGURE 3. Desired temporal variation of reaction force on the index fingertip when a person quickly (a) presses and releases a soft button, (b) passes a junior size basketball from left hand to right hand.

tile feedback is an effective approach for simulating dynamic interaction [12]. Meanwhile we believe that even minimal touch information would effectively improve the realistic experience [13] [14]. Therefore, the first conducted experiments were focused on studying these pulses especially their lower ranges in order to emulate them.

Experiments were conducted to analyse the reaction force in different scenarios. A subject was asked to touch different objects with a 12.7 mm diameter Interlink® Force Sensing Resistor taped to his index fingertip(Fig. 2). The voltage reading across the resistor was monitored by an Agilent 1022 Oscilloscope at 1000 Hz and collected in LabVIEW. The force value is calculated based on the voltage reading and the calibration data provided by Interlink®.

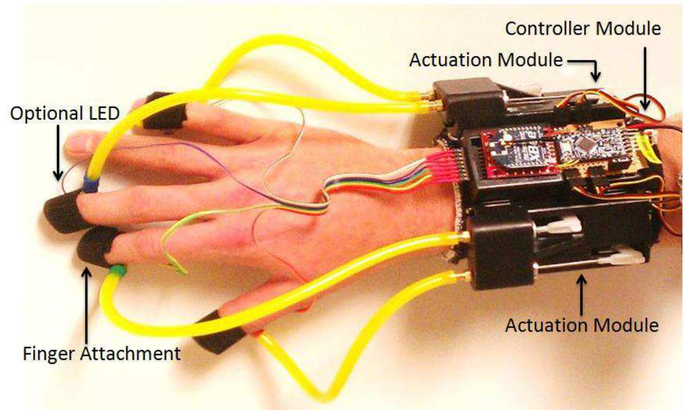


FIGURE 4. The ACTIVE-Hand Prototype.

In one experiment, the subject was asked to quickly press and release a soft button commonly seen on Agilent digital multimeters. The force-time plot is similar to a Gaussian bell curve, as shown in Fig. 3(a). It is a button on the Agilent Digital Multimeter. All the measurements show the similar shape, while the duration varies from 200 ms to 450 ms and the peak force value varies from 1.2 N to 20 N.

In another experiment, the subject was asked to quickly pass a junior size basketball from left hand to right hand. The force resistor remained attached to the index fingertip of the right hand. The most frequent observed shape of the force-time plot is shown in Fig. 3(b). In this temporal variation, there are two major peaks, the first one during catching the ball and the second one during pushing the ball back. The first peak force value varies from 0.7 N to 3.3 N and the second one from 1.8 N to 7.6 N. The duration was observed to be usually around 150 ms to 200 ms. Based on results from these two experiments, we decided that our haptic device should simulate a target pulse that last around 200 ms and peak at least above 1.8N.

THE ACTIVE-HAND

Concept Overview

The ACTIVE-Hand is a pneumatic haptic device that provides tactile feedback in the form of pressure to the user's fingertips. It has two main components, the forearm attachment and the finger attachments. This design achieves two goals: to keep the weight off hand and impose minimal to no constraint on hand motion. The majority of the weight is located at the forearm attachment which carries the actuators and the control circuits. The lightweight finger attachments secure the bladders to the fingers. Although a actual glove format would improve aesthetics and decrease set-up time, at the prototype stage, the finger attachment style allows people with different hand sizes to use the ACTIVE-Hand.

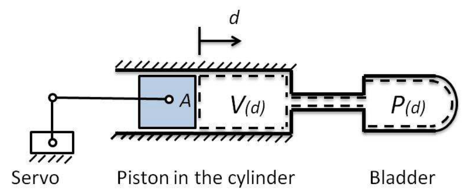


FIGURE 5. The closed loop pneumatic system on the ACTIVE-Hand.

Each bladder is connected to an actuator in the fore-arm attachment by flexible tubing. They form a closed loop pneumatic system. The actuator changes the volume of the air within the closed system, changing the internal pressure. The user then feels the pressure change and the deformation of the bladder at his or her fingertip. The pressure change is not binary; both the magnitude and the rate of change are configurable.

Mechanical Design

The closed loop pneumatic system has a simple mechanical design. The actuator in the forearm attachment is a crank slider. The crank is driven by a servo and the slider is a piston inside a cylinder. A single tube is fixed to the end of the cylinder via a brass air barb. On the other end of the tubing, a latex bladder is attached. The bladder is also bonded to a Velcro strap forming a finger attachment. Alternative designs can replace the crank slider with linear actuators or solenoids. However, for cost, speed and controllability concerns, servo and crank slider were chosen in our design.

The pneumatic system is desired to generate various level of pressure at various rates. This is dependent on the travel of the piston, according to Fig. 5 and Eqn. (1).

$$P(d) = \frac{P_i V_i}{V(d)} = \frac{P_i V_i}{V_i - Ax} \tag{1}$$

Conditions for ideal gas are assumed, and the deformation of the bladder is assumed to be minimal. Neglecting the frequency response of air, the rate of pressure change is then positively dependent on A, acceleration and speed of piston.

We developed a prototype of the ACTIVE-Hand with a 10 mm diameter piston, 3.1 mm inner diameter tygon tubing and 12 mm long 6 mm diameter bladders modified from latex tube balloons. With a safety factor of 1.5, we designed the piston to travel 11 mm to generate a gage pressure of 40 kPa, or 2.7 N of force on the user's fingertip. Since the target pulse is 200 ms long, the piston should have an average speed of 110 mm/s and acceleration of 2200 mm/s^2. The dynamic friction inside the piston is measured to be 0.7 N and the weight of the piston and linkage is 2 gram. It takes at least 3.85 N force to move under

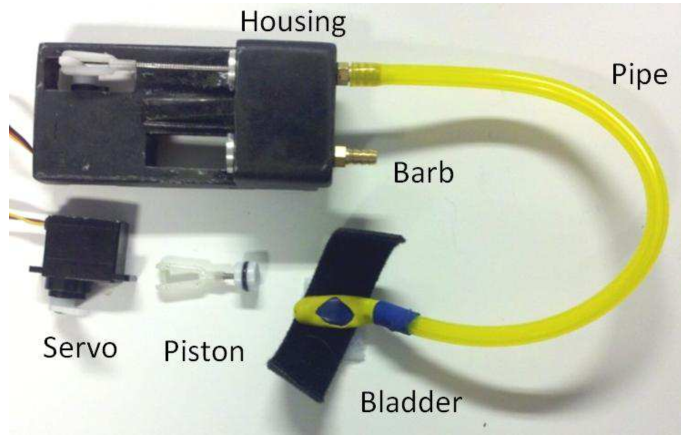


FIGURE 6. Components of the actuation module.

the 40 kPa pressure. For a safety factor of 1.5, we selected the Hitec®HS-65 HB servo (0.11 sec per 60 deg, 2.2 kg-cm, at 6.0 V) and a 17 mm crank to drive the piston. All these components are shown in Fig. 6.

Control System

The ACTIVE-Hand carries an on-board wireless transceiver, a micro controller and a battery. It receives haptic signal wirelessly and commands the servos to act accordingly. In our case, we used a XBee 1 mW Chip Antenna Series 1 as the wireless transceiver, an Arduino Pro 328 Mini as the micro controller and a 7.4 V 800 mAh E-flite®Lithium Polymer battery. The microcontroller outputs reference input signals to the Hitec HS-65 HB Mighty Feather analog servos and the servos update their position. In our initial investigation, we connected 4 servos to the microcontroller. The servos execute individual commands simultaneously. The microcontroller is set updates the position of each servo at 50Hz. If the microcontroller receives a new signal

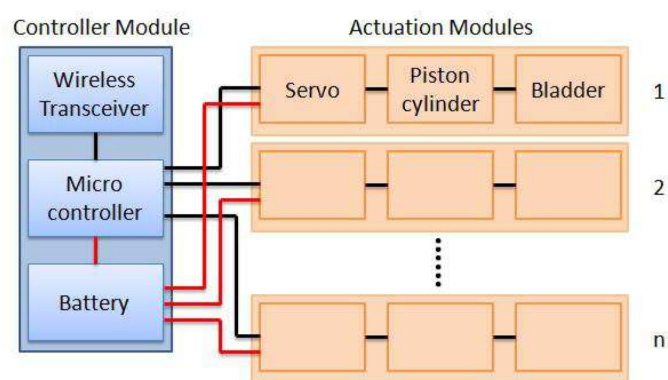


FIGURE 7. The control system of the ACTIVE-Hand.

before it completes rendering the current force profile, it interrupts the current rendering and execute the new one. In between the microcontroller finishing outputting the previous force profile and receiving the next haptic signal, it turn off the servos to save power.

IMPLEMENTATION OF THE ACTIVE SYSTEM

The ACTIVE system is an integration of body motion based 3D gaming system(Kinect) and localized tactile feedback(ACTIVE-Hand). It transforms the users' body motions into the controllers in a 3D virtual environment, allowing them to interact with, touch and feel dynamic virtual objects in real time.

As a demonstration, the ACTIVE system was implemented with a 3D pong game. In this game, A user can move around in a virtual court and hit a moving virtual ball with his or her hands. The user can touch and feel the impact upon the part of hand that press the impact the virtual buttons or balls.

Physical Setup

Designed for the gaming crowd, the ACTIVE system is quick and easy to setup. For our testing, a projector screen and Kinect were placed at the front of the room. A projector and computer were placed on a table to the side of the user. Kinect has a practical depth field of 1.2 to 3.5m and an angular field of view equalling 57 degrees. The user had freedom of motion and gameplay throughout this area. The user is wearing the ACTIVE-Hand on his or her dominant hand and ready to play.

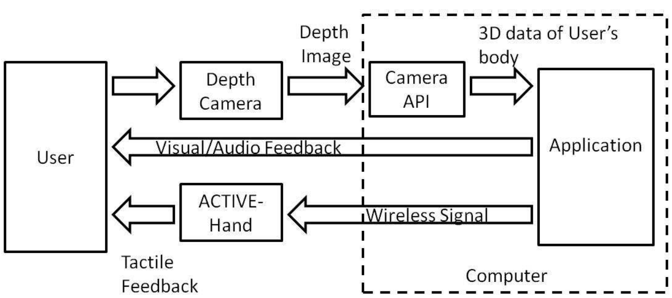


FIGURE 8. ACTIVE system pipeline.

The pipeline of the ACTIVE system is depicted in Fig. . Kinect, or a similar depth camera, collects depth images of the user at 30 Hz and sends them to the computer. Kinect camera APIs(OpenNI) were used to process the depth image for the 3D joint locations of the user's body. Specific Applications then utilize these data as the inputs for the control and haptic rendering algorithms. The computer provides visual and audio feedbacks to

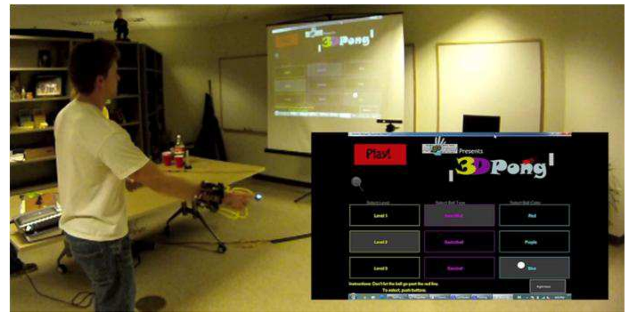


FIGURE 9. Touch button menu interaction. A close-up view of the menu is shown in the lower right corner of the image. The white cursor indicates where the user is pointing at on the menu (lower right corner). The buttons turn grey when selected. The blue LED is a visual indicator of the tactile feedback for the audience.

the user and also sends haptic signals wirelessly to the ACTIVE-Hand. The ACTIVE-Hand then generates the tactile feedback in response.

3D Pong Game

Upon starting the game, the user is presented with a selection menu as shown in Fig. 9. The menu comprises of rectangular buttons to control the game-play characteristics. A play button, three sets of game-play options (Difficulty, Ball Size, and Ball Color), and an option to change the dominant hand are the available selections. The user's dominant hand controls a cursor on the menu. The menu is always defined on a virtual plane within one arm length from the user. When the user pushes on the virtual buttons, they receive tactile feedback on their forefinger (of the selected dominant hand) in conjunction with selecting that particular option.

During game play, the user is mapped to a simple avatar in a virtual room as shown in Fig. 10. A red, translucent paddle, similar to a ping-pong paddle, resides in the user's dominant hand region. Initially the ball moves straight toward the user's dominant hand(paddle). When the user hits the ball, the blue ball flashes green, and then bounces back into the room. In conjunction with the visual stimulus cue, tactile feedback is provided to the user upon the part of hand that collides with the ball. When the user's hand collides with the ball, the ball velocity is changed according to the following condition. Similarly, if the hand has an x or y velocity, a portion of the hand velocity is transferred to the respective x and y velocity of the ball.

$$V_{z,Ball} = \begin{cases} V_{z,Hand}, |V_{z,Ball}| < |V_{z,Hand}| \\ -V_{z,Ball}, |V_{z,Ball}| < |V_{z,Hand}| \end{cases} \quad (2)$$

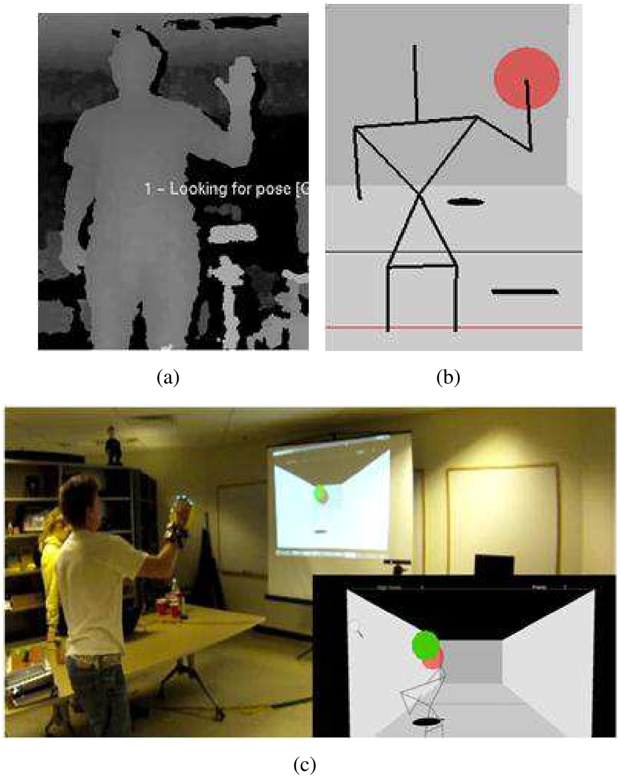


FIGURE 10. (a)Depth image of the user acquired by Kinect. (b)The user is mapped to an avatar with a circular paddle on his or her dominant hand. (c) A user hit the ball in the 3D pong game. A close-up view of the game is shown in the lower right corner of the image.

HAPTIC RENDERING

The Haptic rendering in the ACTIVE system is calculated at two locations, the computer and the ACTIVE-Hand. The computer does the collision detection. It judges when and where to start haptic feedback, and transmit a single start command to the ACTIVE-Hand. The ACTIVE-Hand then completes the interpolation of force variation over the next couple hundred milliseconds and output tactile information without further communication with the computer. We denote this temporal variation of force as force profiles. Prior to running the game application, a library of possible force profiles for tactile feedback is configured into the microcontroller on the ACTIVE-Hand.

This rendering technique suits the ACTIVE system. Given the 30Hz sampling rate of Kinect, much interpolation has to be done to fill in the 0.033 second of blank. As a pneumatic system, it takes the ACTIVE-Hand some milliseconds from receiving a wireless command to outputting the required force. By doing the interpolation on the ACTIVE-Hand instead of the computer, fewer data has to be transmitted for each complete haptic rendering cycle, reducing the cumulative delay.

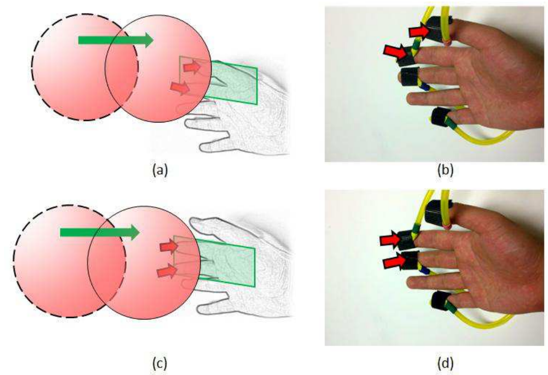


FIGURE 11. Illustrations of segmented tactile feedback. (a) A virtual red ball hits the top portion of the virtual hand. (b) Force feedback is applied to the corresponding portion of the real hand. (c) A virtual red ball hit the middle portion of the virtual hand. (d) Force feedback is applied to the corresponding portion of the real hand.

Collision Detection

In the menu selection, haptic rendering is event-based. When the user is pointing to a button and moving his or her hand forward over a threshold distance, tactile feedback is provided to the index fingertip. According to an open source database OpenKinect, the depth resolution of Kinect which is 2 cm at 2.5 m away. Taking a safety factor of 2.5, we chose 5 cm as the threshold distance. This haptic rendering algorithm is preferred because it avoids undesired selections. If the virtual buttons were defined on a plane and proxy-based haptic rendering is used, users may accidentally select multiple items when they translate their hand across the plane.

The user's hand model is simplified with two assumptions: the palm is always in a vertical position, and the hand is a flat, rectangular shape. The rotation of the hand is approximated by extending the angle of the arm and projecting it onto the Z plane. Because this method of determining hand rotation has a lot of noise interference, a circle instead of a rectangle was chosen to display the user's hand so as to not distract the user from the game with erratic movements. A rectangular shape is still used in the actual algorithm.

Collision detection decides a specific region of the hand where the virtual ball hits. If the center of the ball is within a certain z distance from the hand, then the x and y coordinates of the center of the ball are compared to the hand. If the x and y are within the confines of the rectangle defining the hand, then the ball is considered hit. Tactile feedback is prescribed to the region of the hand that the ball collided with, as shown in Fig. 11. The rectangle representing the hand was divided into three regions, thumb-index, index-middle and middle-pinky. Large balls can hit multiple regions at once and tactile feedback is prescribed to all responding regions.

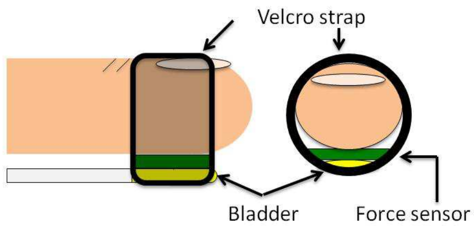


FIGURE 12. Illustration of experiment setup to evaluate the tactile feedback simulated by the ACTIVE-Hand.

Force Profiles

The tactile feedback will be provided based on the speed and predefined properties of the virtual ball in addition to the location of impact. The force profiles for the tactile feedback are experimentally determined to mimic the measured force profile associated with the actions of pushing button and passing a ball. According to the results from Analysis of Touch section, we scanned the design space for the pulses around 200 ms and above 1.8N. In the preliminary study, the suitable parameters of the force profiles for pushing buttons and hitting virtual beach ball at three levels of speed were uncovered. The duration, rate of change and the peak value of the force profile were manually varied while a sport person was asked to play the 3D pong game wearing an ACTIVE-Hand and a force sensor, as shown in Fig. . The subject was informed to hold his hand still while the virtual ball was coming to his hand and imagine he was hitting a beach ball. Then he was asked to comment on if the tactile feedback felt too strong or too weak comparing to what he would expect. Three force profiles were then determined for the 3D pong game. They are all in the form of pulses but with different magnitude and duration, as shown in Fig. 13. The first force profile on the top suited for balls coming at high speed (approximately 8 to 10 m/s). The second force profile suited for balls of medium speed(4 to 8 m/s). The third force profile suited for balls of low speed(2 to 4 m/s) and it also felt right when the subject was pressing buttons on the menu. The range of the ball speed, or the comfortable zone, was also determined to be 2 m/s to 10 m/s. It is very important to synchronize the visual display, audio feedback and tactile feedback to make the interaction between the user and the virtual ball natural and real. Human judges the simultaneity as long as the haptic, audio and visual feedback happens within a certain threshold of time [15]. The 3D pong game program ran at 25.7 frames per second. It is a Dell XPS M1530 laptop (2008) with 4 GB of RAM and a 2 core processor (Intel ® Core™2 Duo CPU T7500 2.2 GHz). It runs Windows ® 7 Professional 64-bit operating system. As a calibration, the visual and audio feedback are offset by two frames, or 78 milliseconds to match up with the tactile feedback.

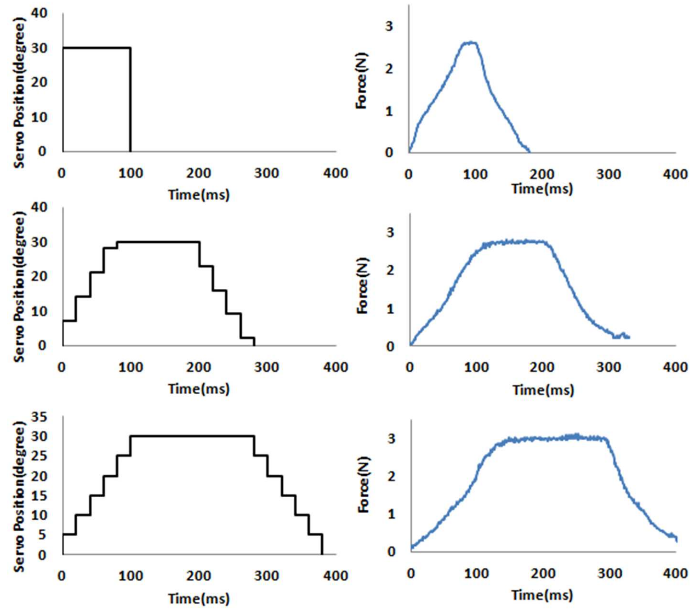


FIGURE 13. The three servo reference position inputs(left) and their corresponding force profiles(right) used in the 3D pong game.

USER STUDY

A user study was conducted to study the value of the ACTIVE-Hand and the tactile feedback in body motion based game. It is evaluated by studying what influence the tactile feedback have over the users' experience and performance. The results shows that tactile feedback allows the users to better use their body as controller, and it makes the game easier and more desirable to play.

Procedure

The experiment compared the effect on user experience and performance of the two conditions of playing the 3D pong game, namely, with tactile feedback and without tactile feedback. Questionnaires were filled and the how the participants behaved in the game were video-taped and studied.

The participants were 8 male volunteers (7 right-handed and 1 left-handed) aged between 22 and 24. All of the participants were students of Purdue University, and they were new to the ACTIVE-system. All of the participants described themselves as athletic (2 were competitive, 4 did sports frequently, and 2 had experience with sports) and they had some experience with ball type sports.

The physical setup of the ACTIVE system is used in the user study. Each participant was asked to play the 3D pong game twice, one trial with the ACTIVE-Hands and one trial without the ACTIVE-Hands, and stop upon scoring 80 hits. To minimize the influence of learning effect on users' experience, the participants

TABLE 1. Group Assignment In the User Study

Group	TF	NTF
Trial 1	with ACTIVE-Hands	without ACTIVE-Hands
Trial 2	without ACTIVE-Hands	with ACTIVE-Hands

are evenly divided into two groups, group TF and group NTF, and their sequence of trials are shown in Table 1. They were told that they are timed, and they would get a 4-second penalty each time they missed a hit. Each time a participant completed one trial, he was asked to complete a questionnaire. Thus each participant completed two questionnaires. When the participants were playing the 3D pong game with the ACTIVE-Hands, they were wearing two ACTIVE-Hands, one on each hand. The same collision detection and haptic rendering were computed for each hand independently. The participants were able to push virtual buttons on the menu and hit the virtual ball with either hand.

User Responses and Observations

The two questionnaires each participant was asked to fill shared the same set of basic questions (Table 2), and there were additional questions in the one they filled after playing with ACTIVE-Hands (Table 3). The participants were asked to rate their responses on the scale of 1 to 7, with 1 being strongly disagree, 4 being indifferent and 7 being strongly agree. Most questions were selected from the usability criteria summarized by Stanney [16].

From the questionnaire results one can tell that the ACTIVE-Hand made it significantly easier for users to coordinate their bodies in the virtual world. It made it easier for users to play the body motion based games. With this device, the users were less likely to feel isolated from the virtual world. The device also made the 3D pong game, which most users commented as boring, desirable again. The users did not find the tactile feedback distracting and they wanted to use the ACTIVE-Hand again. being attached to the fingers and arm, the device made the users to sweat just a little bit more on the hands than they did when playing bare handed. the weight of the device did not result in significant fatigue during the around-12-minutes play. 5 out of the 8 subjects commented that the ACTIVE-Hand was light enough that it did not disturb their play.

In addition to improving the user experience, the ACTIVE-Hand also enhanced their performance. Through observation we found the presence of tactile feedback in the body motion based games allowed the users more freedom and variety in using their bodies as controllers. Throughout the trials, each participant experimented multiple ways to hit the ball without guidance before he converged on the method he was most comfortable with. The first trial could be seen as the learning process, and thus the learning condition for TF and NTF groups were different.

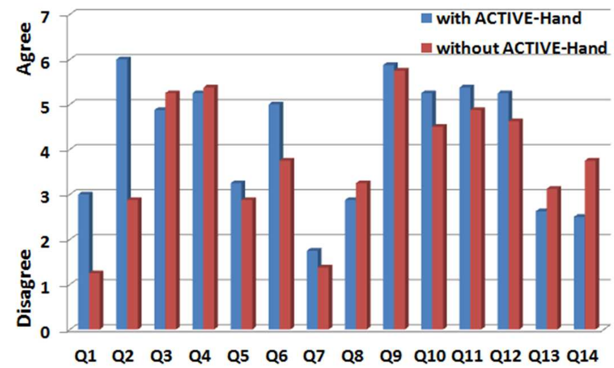


FIGURE 14. The average ratings to basic questions in the questionnaires.

TABLE 2. Basic Questions in Both Questionnaires

Q1	I sweated on my hand
Q2	It was easy to coordinate my body in the virtual world
Q3	It was easy to tell the speed of the ball
Q4	Controlling the speed of the ball was simple
Q5	I often found it hard to locate the ball
Q6	The system did not support my desire to play
Q7	I experience fatigue when playing this game
Q8	I experience frustration when playing this game
Q9	I feel comfortable playing this game
Q10	I feel my physical presence in the game
Q11	I always know where I am related to the ball
Q12	I feel a high level of control of my motion in the virtual world
Q13	It was hard for me to predict the motion of the ball after I hit it
Q14	I feel isolated from the virtual world

TF group learnt how to play with visual, audio and tactile feedback, while the NTF group learnt it with only visual and audio feedback. At the end of their trials with tactile feedback, it was observed that all players had developed their primary method of hitting the virtual ball, and the TF group showed significantly larger variety(Table 4). Moreover, learning with tactile feedback allowed the users to play at a faster pace. The time and

TABLE 3. Additional Questions And Average Responses for Trials with ACTIVE-Hands

	Question	Rating
Q15	The device made it easy to play this game	5.4
Q16	It was easy to tell where the ball hit on my hand	5.6
Q17	The strength of the haptic feedback feels close to the strength of force in reality	4.9
Q18	The haptic feedback is distracting	1.3
Q19	The haptic feedback is not at the right place	4.8
Q20	I want to reuse this device	6.1

TABLE 4. Observed Primary Method of Hitting the Virtual Ball in ACTIVE-Hand Trial

Group TF		Group NTF	
player	Primary method	player	Primary method
A	Arm swing	E	Arm push
B	Wrist flexion	F	Arm push
C	arm extension and block	G	Arm push
D	Arm push	H	Arm push

number of misses it took each player to reach 80 points in his ACTIVE-Hand trial is recorded. For the TF group, this trial was their learning phase, while the NTF conducted this trial after they mastered the game without tactile feedback. As shown in Table 5, the TF group member missed 10 times more than the NTF group member did, as expected from someone who was still learning the game. However, subtracting the penalty time from total time, one will find the TF group completed the task(80 hits) 18% faster. Those who learn to use their body as controllers with tactile feedback learn faster, and play faster.

TABLE 5. Performance Per Subject in ACTIVE-Hand Trial

Group	TF	NTF
Total time(seconds)	311.25	319.5
Number of misses	22.75	12.75
Penalty time(seconds)	91	51
Actual play time(seconds)	220.25	268.5

RESULTS

The ACTIVE-Hand is lightweight, low power, and economical. Fully assembled, the ACTIVE-Hand weighs 315.7 grams and fits onto the users hand and forearm. The majority of the weight and components are on the forearm so the hand is allowed full range of motion and experiences little fatigue. The ACTIVE-Hand generates up to 2.7N of force per fingertip at a rate above 5 Hz. The ACTIVE-Hand provides impulsive tactile feedback approximately 3000 times with one charge of a single 7.4 V battery.

We integrated the ACTIVE-Hand with Kinect, creating the ACTIVE system, an economical and easy-to-setup gaming system. As demonstrated by the 3D Pong game, the ACTIVE system allows users to touch and feel interactions with dynamic virtual objects. In this paradigm, the ACTIVE-Hand is the sole provider of haptic feedback, while the Kinect is the sole sensing device. The interpolation of haptic rendering is completed on the ACTIVE-Hand. For each specific application, predefined force profiles are configured onto the ACTIVE-Hand to relay tactile feedback. User study showed that the ACTIVE-Hand provides valuable tactile feedback to make the body motion based games easier to play and more engaging. The users not only have more freedom to master their own ways of controlling the game, but also have better performance.

DISCUSSION AND FUTURE WORK

The ACTIVE-Hand design has many merits.It is lightweight, compact, and wireless, and it make changes to how people use their body as controller and interact with virtual content. However, Certain aspects can be improved. Although our device generates a noticeable force, the range of force and the rate of change are the constraints. In the 3D pong game the users were able to tell the impact was stronger if the rate of pressure change is higher. We plan to experiment with the combination of different actuation methods, such as the pneumatic system with vibration motors. Vibration motors can impose some high frequency transient effect [3] to help the users perceive the rigidity of virtual objects.

The closed loop pneumatic system is lightweight and the majority of its weight can be moved from the hand to a less sensitive part of the body. Research has shown that when the weight of the haptic device on fingers exceeds certain amount, it will deteriorate touch sensation [8]. The pneumatic system does not have this problem since the actuators are placed on the arm, which is less sensitive to weight. During the user study, all users used the device for more than 12 mins and none of them felt fatigue. In the future work, the maximum tolerable weight on the arm shall be discovered in order to size the design parameter of the ACTIVE-Hand.

The delay effect, audio noise, speed, friction and large numbers of actuators limit the performance of the ACTIVE-Hand.

By varying some design parameters in the pneumatic system, the rate of volume change can be increased and the delay effect can be reduced. In our future work, we will also explore noise cancelling techniques to make the ACTIVE-Hand quiet as well as alternative design architectures to increase the speed and reduce number of actuators.

CONCLUSION

We have developed the ACTIVE-Hand, a completely untethered pneumatic haptic device that is lightweight, low power, and economical. The tactile feedback can be easily configured as the application requires. Through the integration of the ACTIVE-Hand with Kinect, we demonstrated the novel ACTIVE paradigm which enables users to experience dynamic tactile interaction in the 3D virtual environment. The primary goal of this research being realistic and engaging 3D gaming, we achieved it by providing localized tactile feedback in body motion based 3D games.

The authors envision several interesting possibilities in hardware and application design for the ACTIVE-Hand device and consequently the ACTIVE paradigm. The pneumatic system in the ACTIVE-Hand is scalable and it can be attached to any part of the body, potentially leading to full body tactile feedback. Being lightweight and easily reconfigurable, the ACTIVE-Hand can be a new convenient test bed for researches of tactile perception in virtual environment. Being economical and easy-to-setup, the ACTIVE system has significant future potentials especially in body motion based 3D gaming games.

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