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"HapticVive" - A Point Contact Encounter Haptic Solution with the HTC VIVE and Baxter Robot.

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ABSTRACT

With the release of various low cost consumer head mounted displays, such as the HTC Vive, virtual reality (VR) visualisation technology is becoming common place. However, haptic interactions continue to lag behind the visual developments. Touch feedback from the HTC Vive system is only provided by way of vibrations in the physical controllers. There are currently no large scale haptic devices that allow a user to experience force feedback in a room scale VR environment. The research presented in this paper demonstrates this problem can be addressed through the use of a large robotic arm to create an encounter haptic solution. Our haptic VR system uses the HTC Vive and the Baxter robot. Positional data is taken from the Vive controllers and sent to one of the Baxter's 7 degrees of freedom arms, which is used to provide force feedback to the user. An experiment was created where a user pushes wooden boxes off a wall in a VR environment. Several tests were performed. Different virtual boxes with a different simulated weight were simulated by varying the speed at which the Baxter moves away from the user. Results from a thirty participant user study indicate that desirable haptic effects can be achieved in a large room scale environment.

Keywords

Encounter Haptics; HTC VIVE; Baxter Robot; Haptic Feedback; Force Feedback;

1 INTRODUCTION

Within the last five years there has been extremely rapid development and production of new Virtual Reality (VR) technology, specifically with regards to Head Mounted Displays (HMDs). Devices such as the HTC Vive [1] and Oculus Rift [2], currently on the market, offer high resolutions with low latencies. These HMDs allow users to experience immersive VR environments. They are almost identical in terms of resolution and Field of View (FOV). The Vive is designed to be used in a room scale setting, where the user can walk around a VR environment within a set of pre defined bounds. The Oculus can also be used in a room scale setting, though in a smaller working area. Although both the Oculus and Vive use physical hand held controllers for interaction, a major component lacking in both systems is feedback to the sense of touch. The controllers utilise vibrations to stimulate the sense of touch, however these are limited interactions. For example, vibrations cannot render a wall or solid surface. In all simulations the controllers rendered can pass through any surface. Vibrations can only give an indication that the controller has passed through a surface.

The research in this paper proposes to solve the aforementioned limitations of the vibrational feedback by using the Vive controllers and a robotic arm. This robotic arm will provide encounter haptic force feedback to render solid surfaces to a user in VR. We use the Baxter research robot [3] to provide this feedback. Its large 7 degrees of freedom (DOF) arms afford a large working volume and has numerous safety features as standard. These include arm collision detection. The safety features allow for operation in close proximity to a user without a cage, a necessity for haptic feedback.

Providing large, room scale force feedback has yet to be achieved with recent HMDs such as the Vive. Specifically, a solution that can render solid surfaces. Improving haptic interactions helps to increase realism and immersion within VR. The HapticVive system demonstrates that this is possible, and sets the stage for future room scale force feedback solutions.

2 RELATED WORK & BACKGROUND

Haptic devices have been created to provide natural interactions between a user and a virtual environment by rendering forces to the users hands. Haptic devices help improve the operability of tele-operation [4], allow for surgeons to be trained with realistic haptic feedback [5] and also include multi finger approaches providing feedback to more than just the whole hand [6]. Haptics devices should allow for high impedances to be rendered to the user when contact occurs with virtual objects. Also, rendering zero impedance when there is no contact with the environment, thus, rendering the device as transparent as possible. Unfortunately, zero impedance is nearly impossible because the user is always tethered to the haptic device. Achieving a negligible impedance requires that the haptic device has low inertia motors with low gear ratios. However, these may impact force feedback levels. Force control theories, such as impedance or admittance concepts, can also be used to help reduce the impedance in free space [7, 8]. Their reductions are however limited.

Encounter-type haptic devices have been created as a solution to the inability of common haptic devices to render zero impedance in free space, and their lack of realistic transition between free space and contact. Encounter-type devices only collide with the users hand and provide forces if a collision occurs in the virtual environment [9, 10, 11]. When in free space, the encounter-type end-effector is mechanically detached from the user and precisely tracks the position of their hand, granting zero impedance in free space. Encounter-type devices have a range of sizes, or a range of working volumes. The smallest of these employed a 2D circular finger tip encounter haptic interface [12], allowing for feedback around the end of the finger tip. There are a number of large and room scale encounter haptic interfaces for rendering a control panel, juggling simulation and large surface exploration for the palm of the hand [13, 14, 15]. However, none of these incorporate a room scale HMD.

In essence, encounter-type haptic devices are robotic arms. The Baxter robot is a robot made by Rethink Robotics and is comprised of a torso, two 7-DOF arms and a head. The torso is mounted on a wheeled trolley with each arm connected to the torso via an arm mount. Each arm consists of seven rotational joints with the end effector containing a 640 x 400 camera and infrared range detection. The head of the Baxter is represented by a screen attached to the top of the torso also including ultrasonic range detection. Positional accuracy is quoted as ± 5 mm [3]. The Baxter Robot is designed with safety in mind. It has a number of features that allow it to operate in close proximity to humans, without a cage. These features include non-locking joints and sensors in each of the joints to make the robot aware of collisions. The size of the robotic arm, and therefore the working volume along with the safety features make it suitable to act as the force component in an encounter haptics system.

Figure 1: Example of user interacting with the Baxter.

As encounter haptic devices cannot rely on the haptic interface for tracking, they rely on external forms of tracking. The 2D circular finger tip device mentioned previously uses infrared proximity sensors [12]. Filippeschi [16] used the Leap Motion optical tracking device for the tracking element in a seated, non-HMD system for use in medical remote palpitation. The Leap also had the added benefit of increasing tracking and working volume. Infrared camera solutions are also employed in non-HMD roomscale solutions [14, 15], using seven and six VICON MX Motion Capture cameras.

The Vive features five hardware components, a HMD, two base stations and two controllers. The headset contains two screens and has a resolution of 2160x1200 (1080x1200 per eye) and has a refresh rate of 90hz [1]. The base stations are mounted at opposite corners of a workspace up to 4.6m^2, they sweep structured light lasers across the workspace, which are picked up by sensors in the headset and controllers. The vive control system is extremely fast with worst-case latency for head tracking data around 4.444ms (250hz), and worst-case latency for controller tracking data at 4.0ms (250hz). The lighthouse system of tracking is also very accurate, with an RMS accuracy of 1.9mm [17]. This makes the system suitable for encounter haptics, it has both low latency and high accuracy.

There is a real lack of force feedback devices for current generation VR devices. Since many additions to both the Oculus and Vive rely on vibrations. To the best of the authors' knowledge, there are no large scale encounter haptic interfaces for use with HMDs. With the success of the HTC Vive and that 82% of owners use room scale [18], there is motivation to develop room scale haptic solutions. Current haptic devices, such as the well known Phantom device [19], are not suitable for this task due to the small working volume. An encounter type interface comes into its own in a room scale environment and would help to enhance user experience.

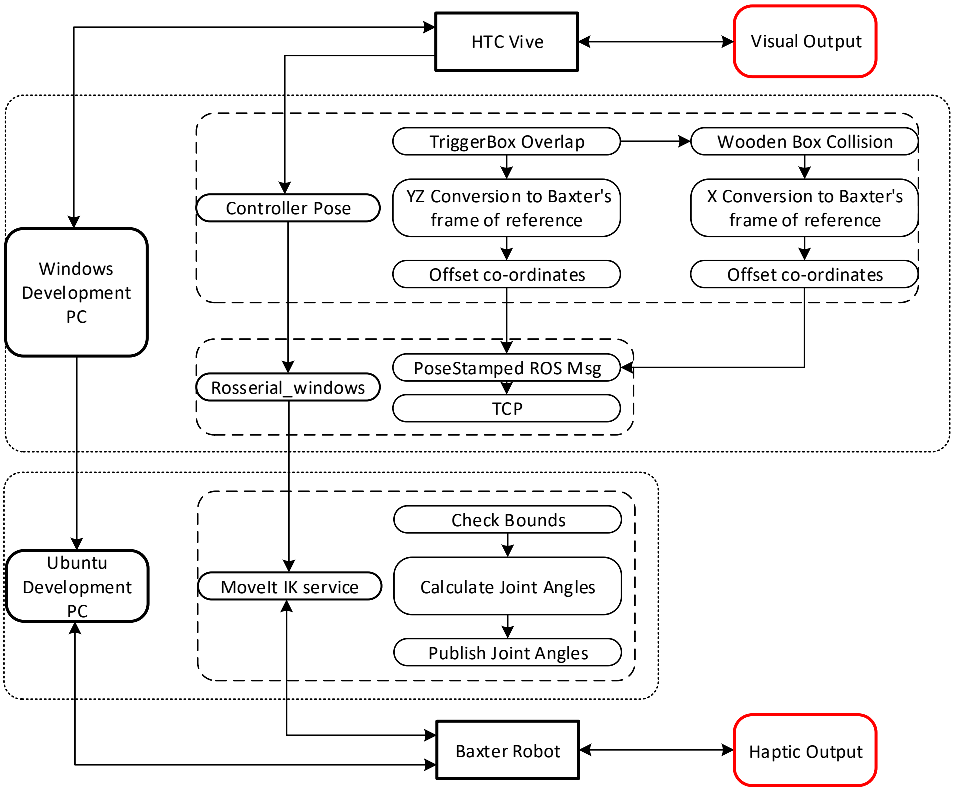

Figure 2: Flow diagram for the HapticVive System. Coordinates pass from the HTC Vive into the Windows PC. Then onto the Ubuntu PC through a TCP Connection. Finally they are sent to the Baxter through ROS.

3 ENCOUNTER HAPTICS SOLUTION

The system is made up from two development PCs, an HTC Vive HMD and a Baxter Robot. The Vive HMD provides the visual component. The Vive's physical controllers provide positional data of a user's hand and the Baxter's robotic arm provides force feedback when required. The computation is split into two halves: one Windows development machine (Windows 10, i7 4790k, GTX 970) is used to run the virtual environment and Vive HMD. The other Ubuntu development machine is used to run the ROS (Robot Operating System) half of the system for the Baxter robot, which can be seen in Figure 2. The Ubuntu PC is running Ubuntu 14.04 and ROS Indigo. ROS Windows header files are used to allow for the use of ROS message types on the Windows development machine. Coordinates are loaded into a PoseStamped ROS message, so the co-ordinates can be sent between development machines using a TCP connection. A socket node along with *rosserial server* is used on the Ubuntu side to allow for communication. This is currently a one way communication. The virtual environment was created in Unreal Engine, primarily used for games design, it allows for quick drag and drop creation with native VR HMD plugins. The VR environment is shown in Figure 3.

The Vive controllers are tracked in 6 DOF within the same work space as the HMD. On the Windows development machine, the Unreal Engine SteamVR plugin can query for the position and orientation of the controller. This data is used to render a model of the controller in VR.

When the controller enters a trigger box, used within Unreal Engine to trigger events, coordinates are sent to the robot. As the controller is therefore in close proximity to a point of interaction. Sending the coordinate data of the controllers when they enter a trigger box is a preemptive measure, as the system is not solely relying on collision data. Were it to rely on only collision data and the robot was a considerable distance from the interaction site, it would not reach the user in time to provide feedback. The robot is always aligned with the controller preempting a collision, provided it is inside a trigger box.

As shown in Figure 2, the pose of the controller is converted onto Baxter's frame of reference, in two parts. Firstly, when the controller is in the trigger box the system converts and sends the YZ portion of the pose, left, right, up, down when facing the Baxter. The Baxter's arm can therefore move along a plane in front of the controller. When a collision occurs in VR between the rendered controller mesh and piece of geometry, the X

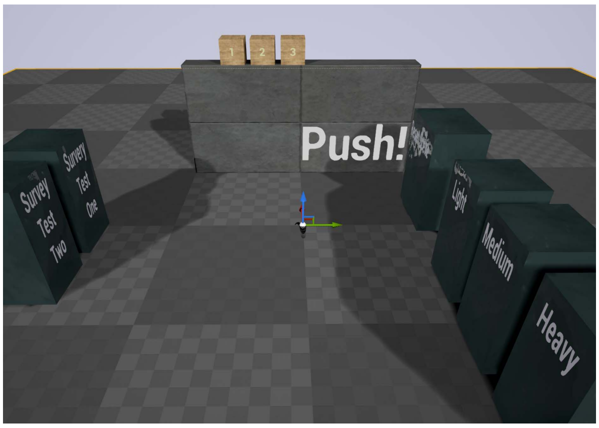

Figure 3: View of the VR environment inside the HMD.

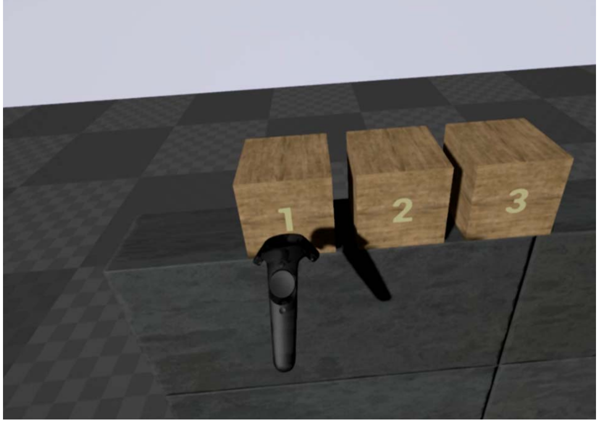

Figure 4: Users perspective inside the HMD.

coordinate of the pose is converted and sent. This is the axis moving in and out toward the user. This allows the Baxter to move in three DOF, and provide force feedback. In order for the Baxter to reach a desired position when the controller is inside a trigger box the Kinematics and Dynamics Library (KDL) inverse kinematics solver is used to calculate joint angles. This is accessed through the Moveit! [20] motion planning framework.

When the Baxter's arm has reached its desired position and an interaction is required, the user needs a physical surface to interact with. A custom end effector is screwed into Baxter's standard electric gripper, a picture of end effector can be seen in Figure 1. The end effector is a sheet of 150*mm* by 100*mm* plywood.

In positional mode the Baxter's speed can be adjusted in a ratio form from 0.1 to 1.0, the larger the number the greater the speed. In order to simulate different weights to the user the speed was altered dependant on the interaction geometry. Within the environment there are various pillars (Figure 3), which are used for functionality within the system, such as resetting the scene, changing condition and the speed of the Baxters arm. The pillars allow for the participant to stay in VR without having to take the HMD off. Allowing for multiple aspects of the system to be tested. A participant places the controller inside the pillar to trigger its functionality.

During initial testing it was observed that based on the inverse kinematics (IK) solution, the Baxters arm speed would slow down when in certain positions. For example, the Baxter has collision detection enabled on its arms and torso, so it cannot hit itself. When confronted with tight, curled in towards itself arm positions, the arms speed slows down, as the arm nears a collision with either itself or the torso of the robot. This has the effect of making items within the VR environment feel heavier, as they take longer to push away, or stop you from pushing them away altogether.

3.1 User Study

30 participants took part in the study. 70% were male with the remaining 30% female. The average age was 35.4 years. 40% of participants taking part in the study answered that they had used a HMD before, and 33% said that they understood the term haptics. Participants of the study were required to be fully mobile, as the study required them to be standing in a room scale environment, and move around in the workspace. The study required the use of their left hand and arm, participants were excluded from the study if they had any minor motor problems. If participants suffered from any illnesses such as epilepsy they were not allowed to take part in the study. During the study no participants were excluded based on the criteria.

The user study was undertaken in order to evaluate the system, in order to measure how well it provided operator feedback. We also wanted to analysis how the Baxter performed in this unorthodox role. The study contained two conditions: For each condition participants were asked to push sets of three boxes off a wall of the virtual environment. As the environment is on a one to one scale with the real world, the wall is one metre tall and the boxes were $0.2m^3$. Using the adjustments in speed of the Baxters arm, we simulated different weights of boxes. For the initial control condition, all the boxes were simulated to weigh the same. In the second condition the boxes got progressively heavier. In the first control condition the arm is set to move at its maximum speed of 1.0, for all three boxes. In the second condition the first box is set at 1.0, the second 0.5, and the third 0.1.

It was explained to the participants that the controller would look the same in VR as it does in the physical world, as the mesh being used to render the controller in VR was an official Vive asset. Time was given for the participant to get used to the HMD and being in the VR environment. Once they were comfortable with the HMD and the environment they were asked to walk forward towards the wall in the environment (Figure 3)

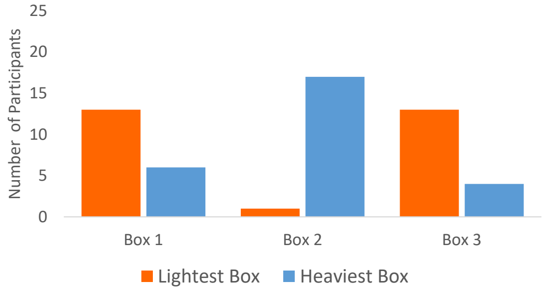

Figure 5: Condition One Results.

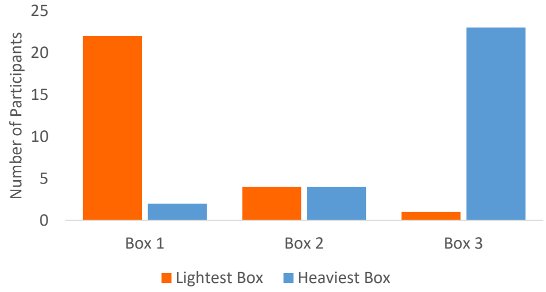

Figure 6: Condition Two Results.

and hold the controller a few centimetres in front of box number one (Figure 4). Participants were asked to slowly push each of the boxes off the wall in order, from one to three. With emphasis made to not attempt to ram the controller through the box, like a punching motion. Upon completion of the first control condition the participant was asked which box felt the lightest and which felt the heaviest. The participant then reset the scene themselves using the pillars placed in the scene (Figure 3). They then completed condition two by pushing the three boxes off the wall in order, and were again asked to note which felt lightest and which the heaviest.

4 RESULTS AND DISCUSSION

The study was developed to gauge the effect the Baxter had on the feedback, in different positions and whether these effects were noticeable to participants.

Dependant measures were analysed in separate one-factor ANOVAs with two levels (Condition: One (No speed variance), Two (Speed Variance)). Comparisons across the levels were made using 95% Confidence Intervals (CI's) generated from the ANOVAs [21]. Both dependant variables displayed a significant effect of condition. Heaviest Box: $F(1,58) = 19.13, p < .001$. Lightest Box: $F(1,58) = 8.97, p = .004$.

The expected outcome was that the participant was not sure which box was heaviest within the first condition. This is because the robot moved away at the same speed for all three boxes and therefore should of felt the same weight to participant. This was in fact not the case for condition one (Figure 5). 56.7% of participants indicated box two felt the heaviest. For the lightest box in condition one 43.3% of participants indicated box one and 43.3% also indicated box three felt the lightest. This is almost a perfect spilt, only one (3.3%) participant felt box two was the lightest, with the remaining 10.0% unsure.

This result is due to the Baxter: The boxes were set up in a manner that had a distinct space between them, they were also quite large, 0.2m^3. The total distance for the length of the working volume across the wall was close to the overall working width of one of the Baxter's arm's. However, when the robot was presented with moving backwards towards itself, in this case for for the second box, the IK solution curled the arm toward the torso of the robot. When presented with these tight joint angles, the Baxter moves more slowly. When the Baxter moves slowly whilst a participant is pushing a box off the wall, the box feels heavier. The use of IK constraints could limit these effects. Anecdotal observations suggest that over elbow positioning would be preferred to under elbow positioning. Where an over elbow position curls the arm from a high elbow point, down and out away from the robot.

When the speeds of the arm are varied in condition two, across the boxes, the results indicate that the participants can pick out the lightest vs the heaviest. With 73.3% and 76.7% picking correctly respectfully. This is shown in Figure 6.

The arm is moving at 10% of its original speed on the third box, this change is dramatic enough for the user to pick it as the heaviest box. This speed is also lower than the reduction in speed that the Baxter creates when its arm in curling in toward its own torso. The arm position therefore has no effect on heavy objects.

As the Vive controllers are not flat front ended, they angle down from the top and angle up from the bottom to meet in the middle at a point. This means there are different ways in which a participant can interact with the wood on the end of the Baxter. If they angle the controller down, they will meet the wood with a flat part of the controller, allowing them to more easily push against the robot. This became apparent with some participants as the controller slid down the wood when pushing the end effector. Some participants tend to push down and forward. A few went as far to completely push down off the wooden plate. This was also an issue when a number of participants attempted to ram through the boxes almost like a punching simulator although they were instructed to slowly push through the boxes.

Although using trigger boxes as preemptive measure to make sure the robot was always aligned with the controller. When a participant moved the controller between trigger boxes, no coordinate data was sent. This left the robot at the previous interaction site. Which occasionally meant the participant had to briefly wait for the robot. Using ray traces from the controller to geometry in the scene is a possible solution to this problem.

Smaller variations in the speed of Baxter's arm may have yielded more beneficial results, along with a greater number of variations. Some participants struggled to push the heaviest box off the wall, with some females opting to use two hands on the one controller when the box stopped moving. The motors in the arm of the Baxter can create a large amount of noise when it moves. Participants were therefore asked about the noise of the Baxter robot moving, whether this was off putting or gave anything away. Most participants were focused on what was presented to them visually and were not influenced or distracted by the noise.

The Vive controllers already include vibration for small interactions, but this breaks down for solid surfaces. The point contact system presented in this work is simple yet effective at bridging this large gap. It also caters to an extremely large working volume, making it ideal for the direction VR applications are going. The Baxter brings some down sides to the effectiveness, in relation to the varying forces that are dependant on arm configuration and orientation, this can be attributed to both its safety features and the simple IK solution employed.

5 CONCLUSIONS

The work reported in this paper has demonstrated that a large robotic arm can be used together with a HMD to augment the virtual reality experience by providing haptic force feedback, and do so in a safe manner. The Baxter is inherently a safer robot, not requiring a cage. However, these safety features come at the price of increased movement latency and wider positioning tolerance. Results from the user study indicate participants can identify changes in weight of virtual objects by changes in speed of the Baxter's arm. When presented with tight joint angles the Baxter's collision detection slows arm speed. Giving the impression that virtual objects are heavier than intended. Future refinement would hope to mitigate the effect on the user of some of these issues, including the correlation of Baxter speed ratios with real world weight and the use of the second arm to create a larger working volume. A lip around the edge of the interaction plate could also be included so the controller cannot slide off the interaction site. A more complex solution with active feedback where the robot pushes toward the participant would help the system be more effective, and provide more uses.

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