A Pointing Device for 3D Interactive Spherical Displays

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***Abstract*—Three-Dimensional (3D) displays have been developed to allow users to view 3D objects from any angle. There are several input interfaces for interacting with this display, such as joysticks and gesture interfaces. However, in order to properly interact with the 3D objects in the display, the input interface needs to obtain its own 3D location from the 3D tracking device. In this study, we propose a low-cost pointing device for a 3D interactive display using an infrared camera and a smartphone instead of a 3D tracking device. The camera is set up at the bottom of the display to detect the contact point between the pointing device and the display surface. The pointing device gets its 3D orientation from the smartphone's built-in Inertial Measurement Unit (IMU). The proposed pointing device enables the user to see the auxiliary line from the device tip from different angles. We demonstrated some 3D pointing applications, such as selecting objects inside the display to show the usability of the proposed pointing device.**

Keywords-VR; 3D stylus; spherical display; virtual reality; perception.

I. Introduction

The increasing use of Three-Dimensional (3D) contents in the media and entertainment industry is providing a catalyst for the development of devices to effectively represent and interact with this content. This study extends our previous research on a 3D pointing device [1]. Over the past decade, this new development has boosted and refreshed interest in Virtual Reality (VR). VR devices such as the Oculus Rift and HTC Vive [2], which are capable of full-body tracking, provide users with a natural interaction with 3D contents in a virtual space.

Apart from VR devices, the development on 3D displays has taken a big step forward with the introduction of light field displays. These displays are generally intended to create motion parallax and stereoscopic disparity, allowing the observer to perceive the scene in 3D without the need to wear obtrusive glasses [3]. Looking Glass [4] is a currently available holographic display system that generates 45 distinct views of a 3D scene using the light field technique. In the future, rapid advances in electronics, optics and photonics are bringing more true 3D display technologies to the market [5].

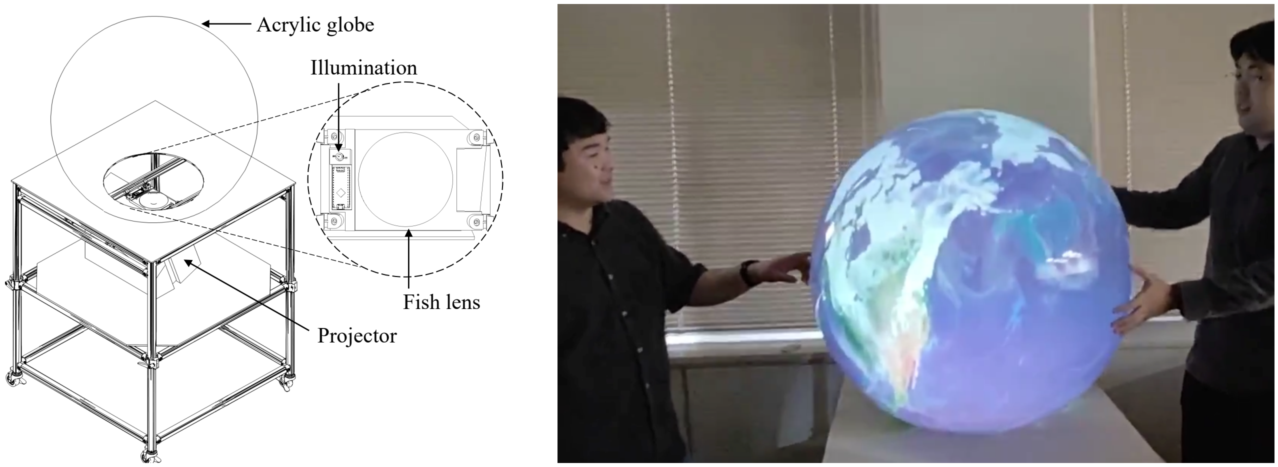
Another attempt to achieve true 3D representation is the use of non-planar displays instead of flat displays. 3D Spherical Display (3DSD) has an advantage on representing 3D objects to be seen from any angle. SnowGlobe [6] and Spheree [7] were developed as perspective-corrected 3DSDs based on a non-planar Two- to Three-Dimensional (2D-to-3D) mapping technique. SnowGlobe uses a single projector and a hemispherical mirror to reflect the image onto the display surface. In contrast, Spheree uses multiple calibrated projectors to project the image directly onto the display surface. Both displays use a 3D tracking device to track the location of the user's head relative to the display, providing a motion-parallax-corrected perspective of the objects on the display. CoGlobe [8][9][10], an upgrade of the Spheree, supports two users to view 3D contents from each own viewpoint using modified active shutter glasses. 3DSDs may have overcome the limited situation awareness of headset VR.

3DSDs can be equipped with a touch interface by optically tracking the user's rear illuminated fingers that appear as blob images when touching the display surface [11]. Each center of the blob has a 3D coordinate (x, y, z) originating from the center of the 3DSD. CoGlobe demonstrated several 3D games using 3D pointing devices such as pointing devices and rackets. The OptiTrack system [12] tracked the 3D location and orientation (x, y, z, *pitch*, *yaw*, *roll*) of multiple passive reflective markers attached to those devices. Hereinafter, the information about the 3D location and orientation is simply referred to as Six-Degree of Freedom (6DoF). This system also uniquely identified and labeled each group of markers attached to each device.

Attaching multiple reflective markers to a pointing device can degrade its functionality. In addition, in order to estimate the 6DoF, those markers needed to be connected to each other like branches, which increased the shape of the pointing device and made it difficult to use. Instead of reflective markers, Augmented Reality (AR) markers can be used to estimate the 6DoF of a pointing device, such as the DodecaPen [13]. However, due to the shape of the 3DSD, the pointing device is often hidden from the camera used to track the AR markers, making it impossible to estimate the 6DoF.

In this study, we propose a pointing device suitable for a spherical display by using a touch interface to acquire the 3D location and an Inertial Measurement Unit (IMU) to acquire the orientation. The orientation data is calibrated using the Motion Platform and the corrected data is sent to the computer controlling the 3DSD and combined with the 3D location obtained from the touch interface.

The rest of this paper is organized as follows. In section II, we describe the 3DSD hardware and software developed for this study. Section III introduces our approach to implement the pointing device. Section IV describes our experiment results. Section V discusses about the further enhancements to the proposed pointing device. Finally, Section VI presents our conclusions and future works.



(a) The hardware design of our 3DSD

(b) The globe

Figure 1. Our 3D spherical display (a) and the globe (b) projected onto the display.

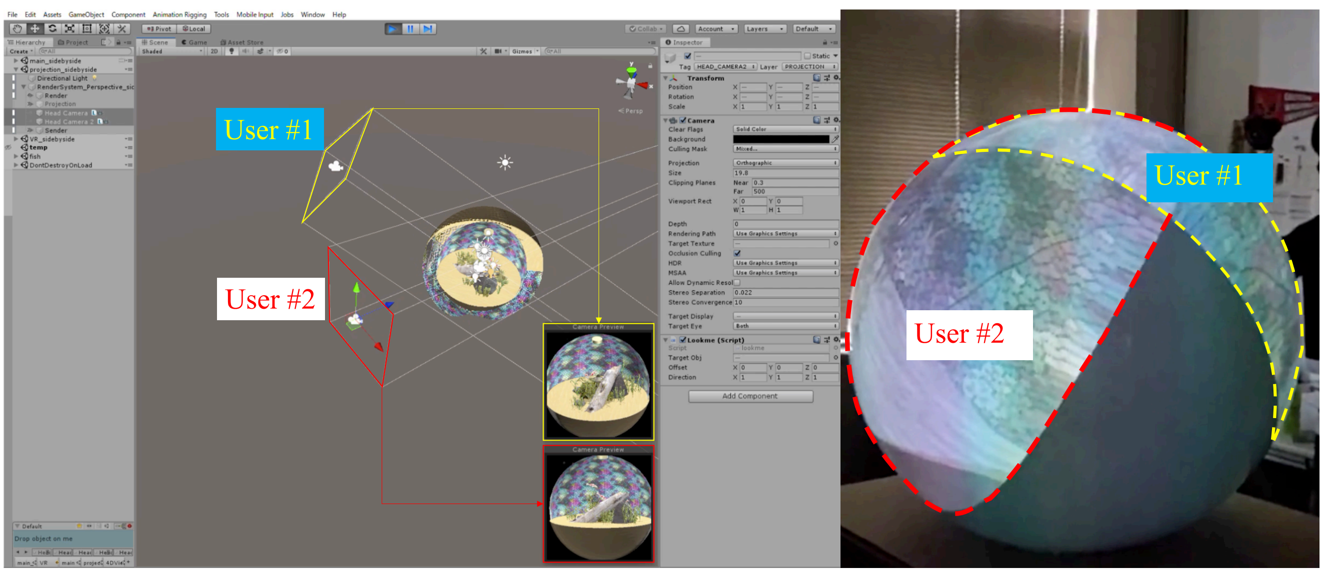


Figure 2. Our 3DSD software program based on the Unity 3D platform.

II. The 3D Spherical Display for This Study

A 3DSD was created for this study using a single projector. Figure 1(a) shows the hardware design of the 3DSD. We used a spherical acrylic lighting case (acrylic globe) as the display material. The interior of the display was painted with rear-projection acrylic paint, so that images projected from inside are visible from the outside of the display. A 3D projector with 4K resolution to was used to generate a high-resolution image onto the display. A fisheye lens was installed between the projector and the acrylic globe to spread the image from the projector to the entire surface of the interior of the spherical acrylic. In order to make the display touchable, we placed a wide-lens infrared camera at the bottom. Since the axes of the camera and of the fisheye lens are different, we aligned these axes using an affine transformation. For the infrared illumination, we installed a high-power infrared LED at the opposite side of the camera. Figure 1(b) shows the globe on our 3DSD.

To make it easier for users to visualize 3D objects, we have created a software program based on the Unity 3D Platform that allows any 3D application running on the platform to be displayed on the 3DSD. Figure 2 shows how two users view a 3D scene from different perspectives. As shown in the figure, the software program generated images for each viewpoint and projected those images onto the surface of the 3DSD. The two images appear to be superimposed, but each image is displayed at a different timing. Therefore, if the user uses shutter glasses, the images at each timing can be viewed separately. Currently, the HTC

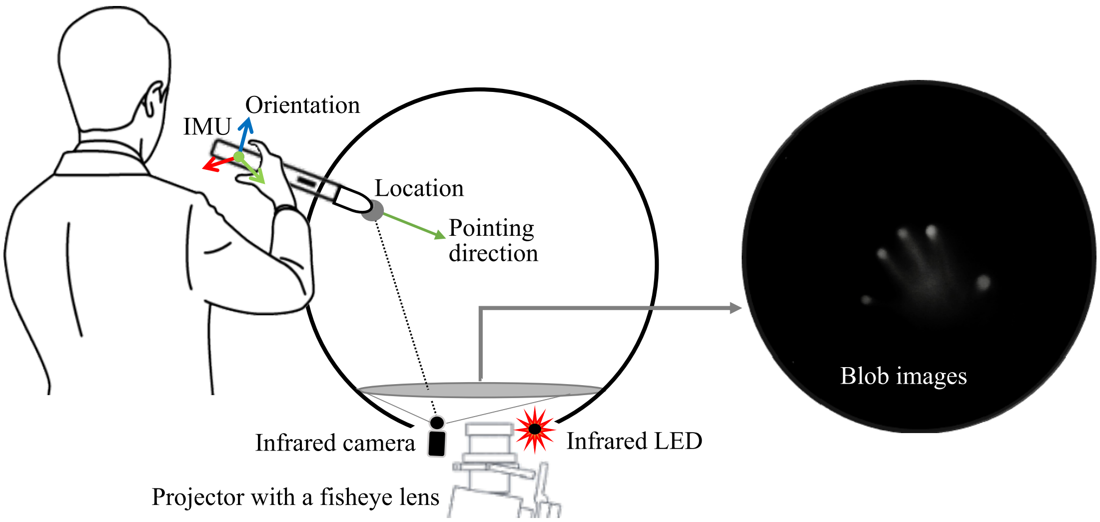


Figure 3. The mechanism of the proposed pointing device.

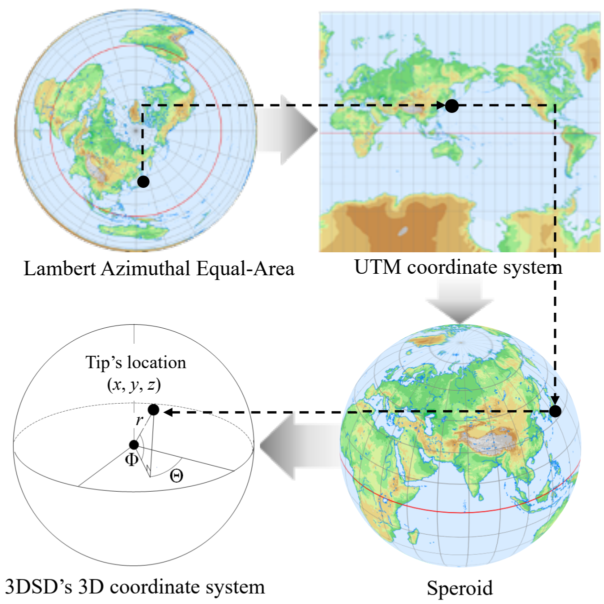


Figure 4. 3D coordinates of the tip of the pointing device.

Vive Tracker [14] needs to be attached to the user's head to determine the user's perspective. In the future, we plan to simplify the tracking system by replacing it with a 3D face tracking based on a vision camera.

III. Our Proposed Pointing Device

Figure 3 shows a scene in which the proposed pointing device is used on a 3DSD. The camera for the 3DSD touch interface captures any blob images on the 3DSD surface. The proposed pointing device does not use a 3D tracking device such as motion capture, but acquires the location based on the blob image detected by the infrared camera and the orientation based on the IMU. The details of the calculation to determine the location and orientation of the pointing device are as follows.

A. Detecting the location of the tip of the pointing device

When the tip of the pointing device touches the surface of the 3DSD, the blob image corresponding to the touched area is extracted to localize the tip's location. This process involves binarizing the blob image to form a contour at the boundary and fitting an ellipse to the contour. OpenCV (opencv.org), an open-source computer vision software library, is used for this calculation. Here, the coordinate of the tip of the pointing device is calculated as the center coordinate of the ellipse.

We perform the following coordinate transformations to convert the coordinates of the tip of the pointing device mentioned above into the 3DSD's 3D coordinate system. At first, since the image in the 3DSD is projected according to Lambert Azimuthal Equal-Area Projection, the coordinates of the tip of the pointing device are converted to this projection. Next, these coordinates are re-projected into the Universal Transverse Mercator (UTM) coordinate system and mapped onto spheroid, which represents the 3D coordinate system of the 3DSD. Figure 4 shows a series of the above transformations. The world map was used as the background image projected onto the 3DSD to make a better understanding of these transformations.

In our system, the blob image is extracted for everything that touches the surface of the 3DSD, but currently, we do not distinguish between the user's fingertip or the pointing device. Therefore, when using the prototype of this pointing device, the 3DSD should not be touched except by this device.

B. Getting the rotation of the pointing device

In this study, we prototyped the pointing device using a mobile device, the iPhone 7. As shown in Figure 5, we set up a pointing stick on the top of the iPhone 7 and attached a rubber to the tip to touch the 3DSD. The pointing device gets

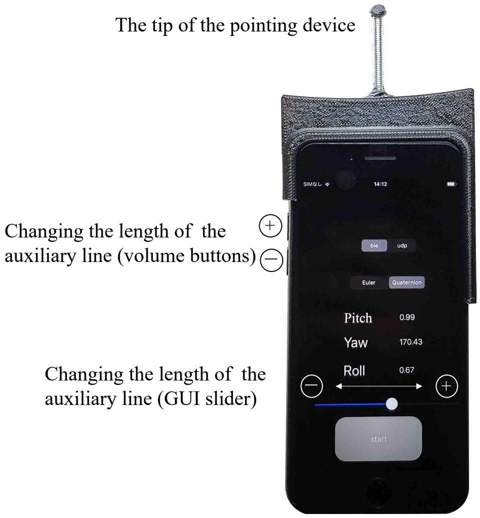


Figure 5. The proposed pointing device for the 3DSD.

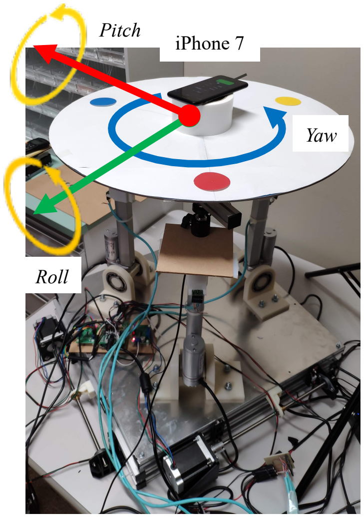


Figure 6. The Motion Platform built for this study.

its own orientation (*pitch*, *yaw*, *roll*) from the iPhone 7's built-in IMU. This information is transmitted to the 3DSD via Bluetooth of the iPhone 7. In this way, this integration of location and orientation information allows the pointing device to have 6DoF information. Using this information, the 3DSD software system will be able to calculate the posture of the pointing device and project an auxiliary line from its tip according to the user's perspective. Here, the length of the auxiliary line can be adjusted with the audio buttons on the iPhone 7 or the Graphical User Interface (GUI) on its screen.

The iPhone 7's built-in IMU includes a compass and a gyroscope sensor. However, to make the pointing device works properly, these sensor values must be calibrated in advance. In this study, we constructed a simplified Stewart Platform (Motion Platform) to calibrate the rotation information obtained from the IMU of the iPhone 7. Although this simplified platform has only three actuators instead of the six used in the original form, it is enough as a validation device for this study.

Figure 6 shows the calibration of the iPhone 7 on the Motion Platform. The calibration analyzes the difference between the rotation angle from the IMU and the rotation angle of the Platform. For calibration, the Motion platform was used to perform 27 arbitrary motions only on pitch and roll angles. The reason for not changing direction to the yaw angle is to measure the stability of the IMU when measuring the yaw angle. Since the changes in the yaw angle are the result of the changes in pitch and roll, there will be less changes in the yaw angle. Figure 7 shows orientation angles derived from the IMU after being calibrated using the Motion Platform. Figure 8 shows the relationship between the rotation angle of the Motion Platform and the rotation angles of the iPhone 7. Despite the variability of the pitch and roll angles of about ± 10 degrees, the variability of the yaw angle is limited

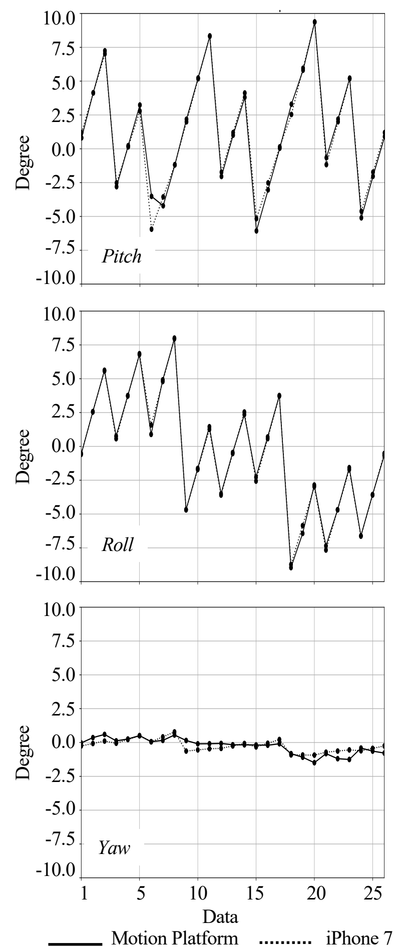


Figure 7. Values of orientation angles derived from the IMU after being calibrated using the Motion Platform.

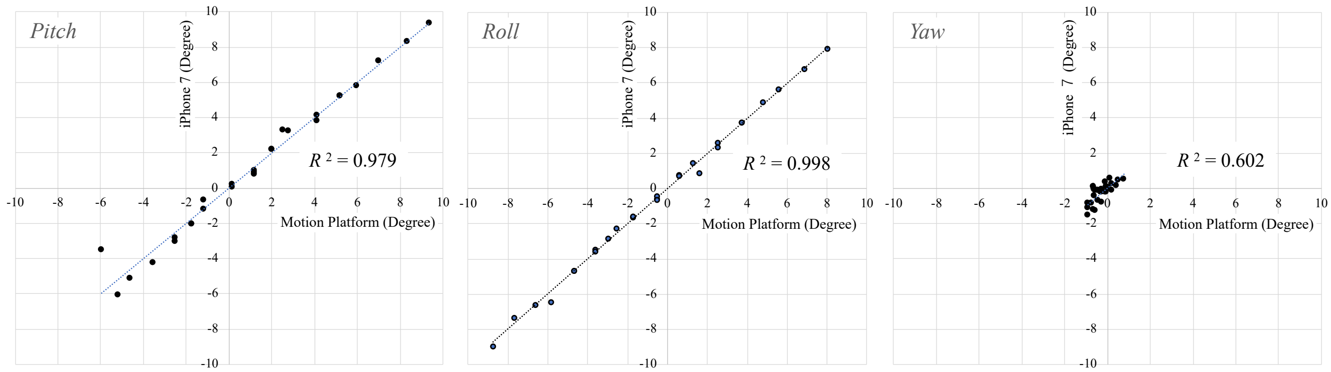


Figure 8. The relationships between orientation angles of the Motion Platform and the iPhone 7.

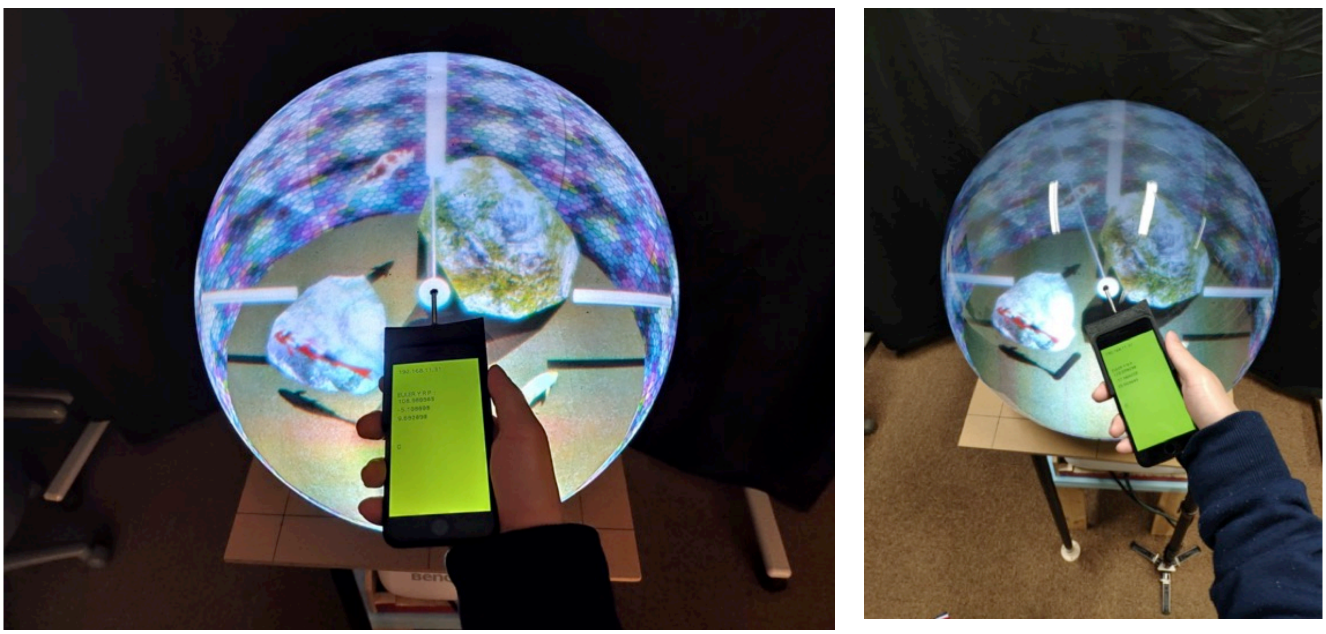


Figure 9. Our working pointing device.

to about ±2 degrees. There was a high correlation between the pitch angles, $r(25) = .99$, $p < .001$, with a $R^2 = .979$. Similarly, there was also a high correlation between the roll angles, $r(25) = .99$, $p < .001$, with a $R^2 = .998$, and between the yaw angles, $r(25) = .78$, $p < .001$, with a $R^2 = .602$. These results indicate that the IMU built into the iPhone 7 is accurate enough to perform interactions that require absolute orientation.

Figure 9 shows the proposed pointing device that works with the 3DSD. The HTC Vive Tracker was attached to the camera to capture this image from the correct perspective. To give users a strong impression of motion parallax, we attached a wallpaper pattern on the back of the virtual fish-tank. From the camera's perspective, the auxiliary line of the pointing device extends in the correct direction according to the orientation of the device. The volume button or slider as shown in Figure 5 allows the user to adjust the length of this line.

IV. Experimental Results

We evaluated the proposed pointing device in terms of accuracy, pointing stability, and user experience. A 51 cm diameter 3DSD was used in the experiment. The display, pointing device and user perspective coordinate systems were calibrated using the HTC Vive tracker. The 3DSD runs on a desktop computer with a 3.6 GHz CPU, 32 GB of RAM and a GTX980Ti graphics card.

A. Pointing Accuracy

In the 3DSD, the accuracy of the pointing device is required for operations such as selecting a 3D object. In the case of the 3DSD with a diameter of 51 cm, one degree of

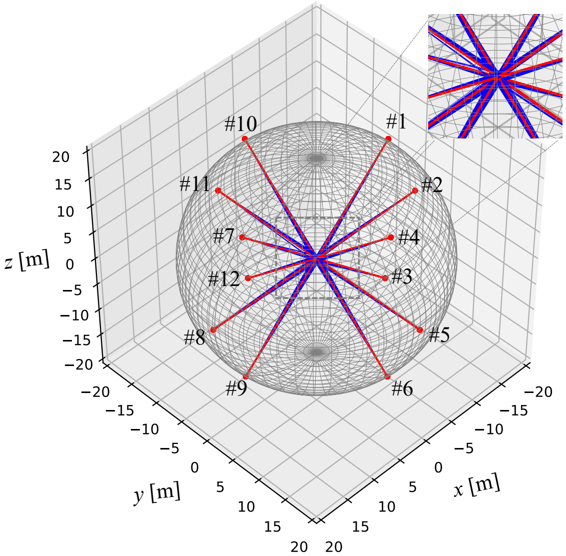


Figure 10. The resulting vectors (blue) from the pointing device tip and their corresponding ground truth (red).

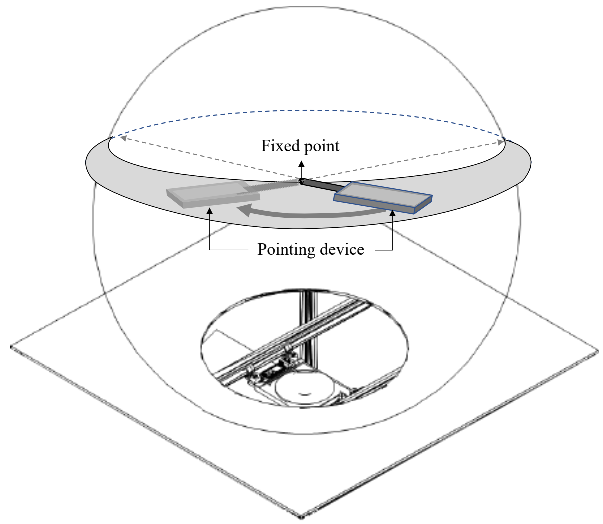


Figure 12. Schematic diagram of the pointing experiment in yaw angle direction.

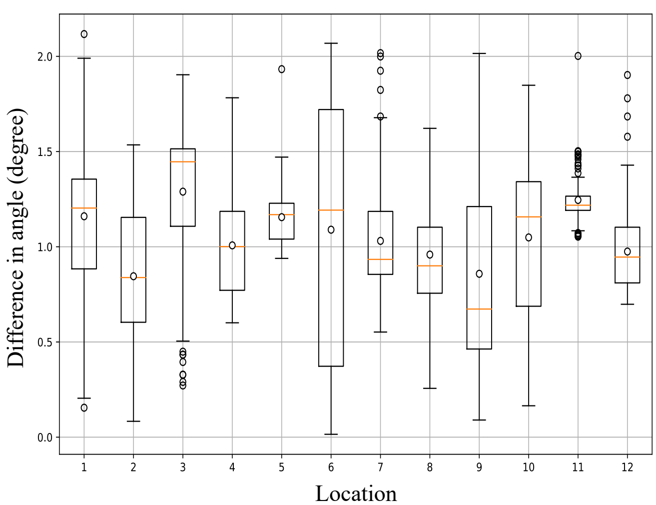


Figure 11. The distribution of the angle differences at each of the 12 locations.

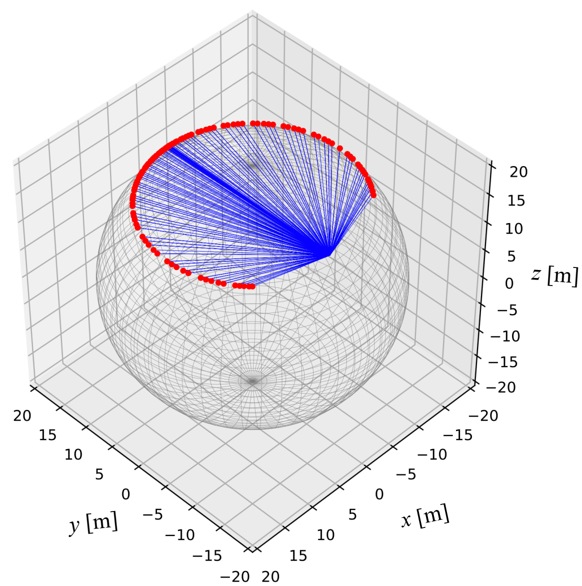


Figure 13. Intersection points of the vectors from the pointing device tip and the display surface.

pointing error corresponds to a deviation of about 1 cm at the center of the 3DSD. In order to evaluate the accuracy of pointing, 12 arbitrary locations on the 3DSD surface were selected, and the pointing device was set from these locations towards the center of the display. At each point, vectors representing the pointing direction were recorded for two seconds, and the difference with the vector connecting the pointing point and the center of the 3DSD, hereafter referred to as the ground truth vector, was analyzed. Each measurement was sampled at 60 Hz, resulting in 120 vectors.

Figure 10 shows the 12 locations used for the evaluation and vectors of the pointing device pointing to the center of the display from those locations (blue lines). The red lines show the ground truth vectors. A small discrepancy can be observed between the red and blue lines. Here, we took the inner product of both vectors and quantified the difference in angles. Figure 11 shows the distribution of the angle differences at

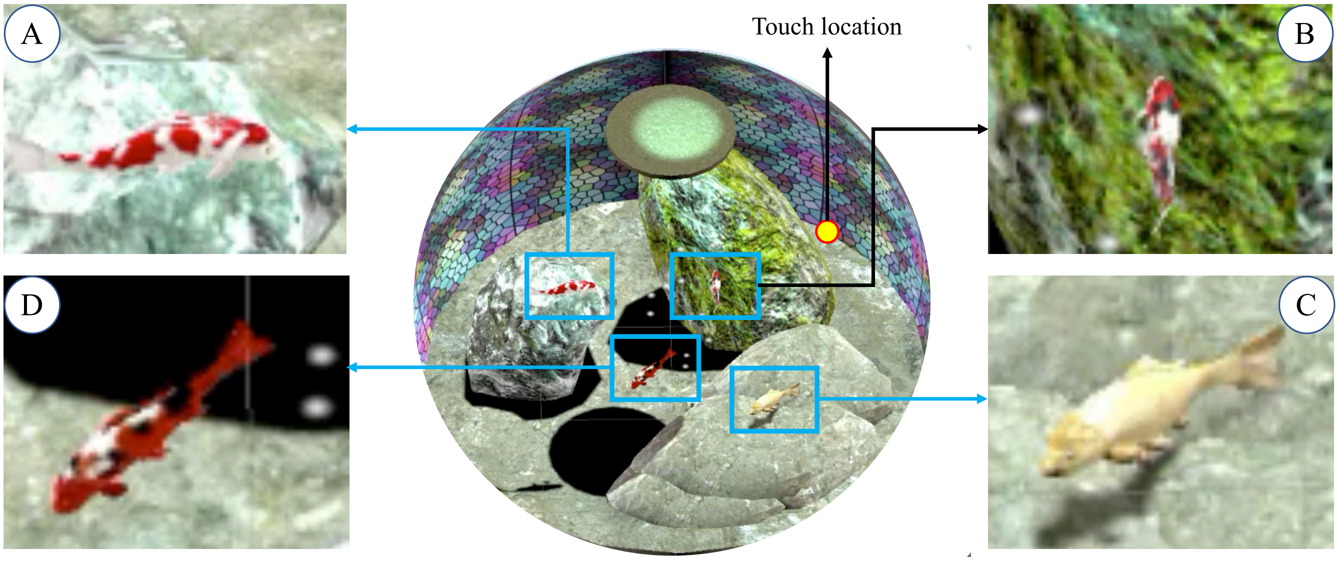


Figure 14. The virtual fish-tank for the experiment.

TABLE I. TIME BEING TAKEN BY THE SUBJECT TO POINT EACH FISH.

Subject	Fish			
ID	A	B	C	D
1	8.4	3.4	5.5	4.9
2	7.5	2.6	3.6	3.3
3	4.3	2.5	5.1	4.6
4	3.5	10.6	4.4	4.8
5	8.4	4.3	5.3	4.9
6	5.9	4.6	4.4	5.2
7	7.8	3.5	4.1	3.8
8	6.9	3.2	2.9	3.8
9	10.6	3.7	3.7	4.8
Mean	7.03	4.26	4.34	4.45
StDev.	2.204	2.458	0.844	0.663

(seconds)

each of the 12 locations. The circle inside the interquartile range represents the mean value of the data. The median values and interquartile ranges varied by locations. However, the median and mean values in total measured 1.08 and 1.05 degrees, respectively. These values correspond to about 1 cm at the center of the 3DSD. The range of quartiles is at most 1 degree or less, except at the sixth location. At the sixth location, pointing diagonally upward might be the cause of the increase in the differences. In practical use, most users are not aware of any differences within this range. The one-way Analysis of Variance (ANOVA) shows that there is a significant effect of the location on the pointing accuracy [$F(11, 1392) = 2.26, p < .01$].

B. *Pointing Stability*

In the previous calibration using the Motion Platform, the correlation between the IMU's yaw angle and the measured yaw angle was the lowest compared to the pitch and roll angles. In order to investigate how this result affects the stability of the pointing operation, we performed an experiment of pointing solely in the yaw direction.

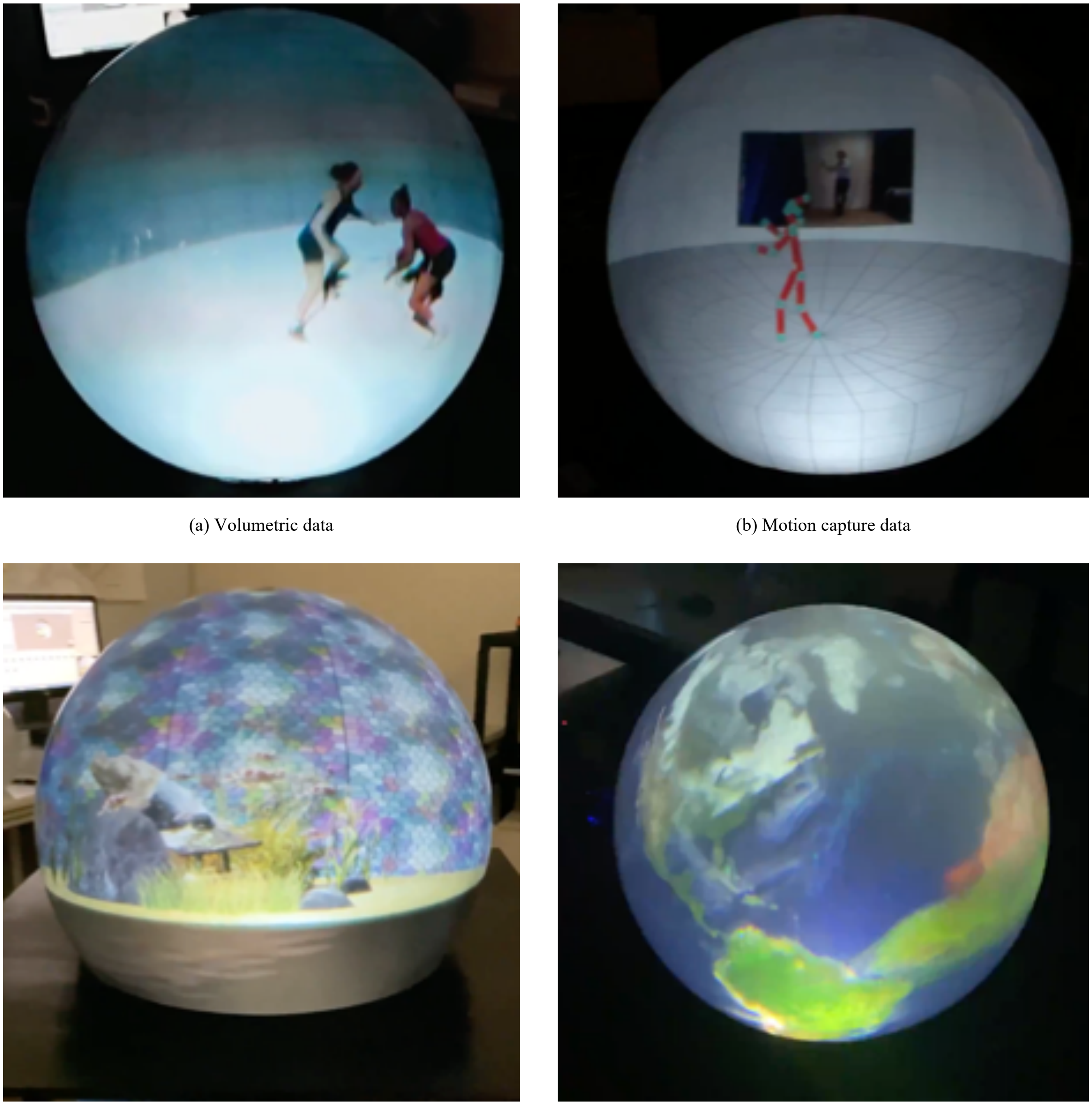
Figure 12 shows a schematic diagram of the experiment. The pointing device is placed on a board placed on the side of the 3DSD to allow pointing only in the yaw angle direction. Here, the pointing device was rotated ± 135 degrees with respect to the center of the 3DSD and the vectors representing the pointing direction were recorded. In total, 1,147 vectors were collected during the operation.

In order to verify the pointing stability, we calculated the intersection points (x, y, z) of these vectors with the 3DSD and fitted a plane $f(x, y) = z = ax + by + c$ to these points using the least squares method. The maximum absolute value of the residual was measured 0.20 cm. This small error means that the pointing vector changes smoothly in the yaw direction and the proposed pointing device is sufficiently stable. Figure 13 shows the distribution of the intersection points on the 3DSD.

C. *Object Selection*

We conducted an experiment to select objects in 3DSD using the proposed pointing device. For the experiment, we constructed a virtual fish-tank in 3DSD and placed four fishes at a distance from each other. We measured the time required to select every fish.

Nine students of the Faculty of Software and Information Science of Iwate Prefectural University participated in the experiment. Each subject randomly selected each fish using the proposed pointing device. However, in order to avoid gaps in results due to differences in pointing distance between



(a) Volumetric data

(b) Motion capture data

(c) Virtual fish-tank

(d) 3D digital globe

Figure 15. Various 3D contents that can be displayed onto the 3DSD.

subjects, we had all subjects start pointing at the same point. When the selection was successful, the color of the fish changed automatically and the time since the start of pointing was recorded. The experiment ended when all four fishes have been pointed out successfully.

Figure 14 shows the virtual fish-tank for the experiment. The "touch location" is a location to start to point to a fish, regardless of the location of the fish. The four fishes (A, B, C, D) are 34.9 cm, 22.6 cm, 23.7 cm, and 21.8 cm away from this point, respectively.

Table I shows the time being taken by each subject to select each fish. While the average time required to select fish in B, C, and D takes about 4 seconds, most subjects spent the most time to successfully select the fish A. We considered that it is a reasonable result since the fish A is the farthest away from the touch location. When selecting an object that is far away, a small amount of slippage in the pointing angle can reduce the pointing accuracy to the object. The one-way Analysis of Variance (ANOVA) shows that there is a significant effect between the pointing locations on the time taken by subjects to successfully point to a fish [$F(3, 32) = 4.46$, $p < .01$].

V. Discussion

Various spherical displays have been proposed in the past decade. The main purpose of developing these displays was to allow users to view content from various angles. To our knowledge, Sphere [15] is the first 2D spherical display that introduced multi-touch interactions, such as dragging, scaling, flicking, and rotating. This multi-touch function provides the same level of interaction as that of an ordinary planar display. However, as the use of 3D content increases, the direction of development of spherical displays has changed from 2D to 3D. Currently, there are some companies producing spherical displays, such as Global Imagination [16], PufferSphere [17], and ArcScience [18].

In 2011, SnowGlobe [6] was demonstrated to be the first 3DSD with a fish-tank VR. It has the same multi-touch functionality as the Sphere, allowing for interaction with 3D objects. However, interaction with 3D objects is likely to take advantage of the depth information, which requires a complex system to realize. Spheree [7] demonstrated 3D gestures using an optical motion capture device. Currently, CoGlobe [8] might be the most advanced 3DSD that allows two users to interact with the display at the same time. However, as long as the 3D interactions rely on expensive motion capture devices, the 3DSD may not become widely available. A 3D pen stylus that does not require a motion capture device such as the Touch™ Haptic Device [19] may be used to perform 3D interaction with the display within a certain range. However, its arm limits the work area.

This study extends the touch interface to enable 3D interactions without the use of a motion capture device. For this purpose, we have built a new 3DSD that has the same functionality as CoGlobe. Our proposed pointing device combines the 3D position on the display surface detected by the touch interface with the orientation measured by the IMU to obtain the 6DoF. Due to the high precision of recent IMUs, such as the one built into the iPhone 7, we believe that it is reasonable to obtain the orientation information of the pointing device from the IMU. Our calibration results using the Motion Platform indicate that the IMU built into the iPhone 7 is accurate enough to perform interactions that require absolute orientation.

The 3DSD has the potential to represent a variety of 3D contents, such as volumetric data [20], motion capture data, virtual fish-tank, and 3D digital globe, as shown in Figure 15. Since the proposed pointing device uses a mobile device, its functionality can be further enhanced by software application programs on the device. For example, after selecting a 3D object, gestures such as rotating and scaling can be performed on the mobile device screen to manipulate the 3D object. The capability to control the length of the auxiliary line from the tip of the pointing device may allow the user to sculpt or slice the 3D objects. Moreover, by using the haptic sensor inside the mobile device, the user can receive a haptic feedback when touching a 3D object.

VI. Conclusion

In this study, we have proposed a new pointing device that can be used to interact with a 3D spherical display without using a motion capture device. Our proposed device is characterized by the two different sources to calculate its 6DoF. They are a touch interface to acquire the location of the device tip and an IMU to measure the orientation of the device. We built a Motion Platform with three actuators to calibrate the IMU. Our experiments have confirmed the pointing accuracy and stability for the device.

The proposed pen has not yet been studied in detail in terms of resolution and sensitivity, but we will further experiment to clarify it in the future. We will also extend the functionality of the proposed pointing device as an interface in virtual surgical training based on a spherical display.

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