Ultrasonic Glove Input Device for Distance-based Interactions

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ABSTRACT

This paper presents distance-based interactions for wearable augmented reality systems enabled by an Ultrasonic Glove input device. The ultrasonic glove contains a tilt sensor and a pair of ultrasonic transducers in the palms. The transducers are distance-ranging sensors that emit ultrasonic waves from the palm of the hand. We developed distance-based interactions including modeling by measurement, numeric entry, and affine transformation interaction techniques. The interactions are based on natural gestures such as facing the palms towards each other or other surfaces. Virtual models of physical objects are created by the user specifying the dimensions with hand gestures. Distance data from the ultrasonic transducers is combined with orientation data to create dimensional vectors and construct models. We conducted an evaluation for the techniques and input device, including a pilot experiment, a user study, and an expert study session. The results indicated that for the task of modeling physical objects, the ultrasonic glove reduced completion time and, in many cases, task error. Our techniques can be generalized to different sensor technologies.

Keywords: ultrasonic gloves, distance-based techniques, modeling, manipulation.

Index Terms: H.5.2 [Information Interfaces and Presentation]: Input devices and strategies; I.3.6 [Computer Graphics]: Interaction techniques.

1 INTRODUCTION

Models play an important role in augmented reality (AR) systems [1] to improve the AR experience by supporting the algorithms that provide improved occlusion effects [2], more accurate registration [3], and improved augmentation of corresponding physical objects. Even with the large body of research exploring modeling techniques for AR systems, the majority of models used by AR systems are created using traditional desktop systems. AR users are constrained to the role of a consumer of the models with limited capability for creating and modifying them. Two major techniques have been investigated, namely computer vision and direct manipulation.

A notable example of action at a distance is the AR working planes technique by Piekarski and Thomas [4] to create polygonal models of outdoor buildings using wearable computers. The technique defines an outline model of a building by intersecting a collection of planes, which are created by the user sighting along the surfaces of the building to be modeled. Bastian et al. [2] developed a modeling approach using segmentation algorithm from computer vision. The 3D shape of the object is reconstructed based on the silhouette of the object from various angles, which as been segmented from the background. Computer vision techniques cannot model purely virtual objects, i.e. there is the requirement of physical object to model. AR modeling techniques are still facing the challenge of precision, which is an established advantage of traditional CAD (Computer Aided Design) programs.

A major challenge for AR systems, especially for outdoors, is the development of intuitive input devices. The traditional keyboard and mouse are not suitable due to the mobile nature of the outdoor AR system. Immense research effort in the area of input devices has produced a range of devices in various form factors, with different types of sensors used for a diverse set of techniques [5]. We are particularly interested in glove-based input devices for their support of natural, intuitive, and hands-free interaction. Our Tinmith wearable AR system [6] currently uses a pair of pinch gloves with fiducial markers on the thumbs for cursor-based manipulation technique. The head mounted camera detects the markers to control two cursors on the user's viewport. Throughout our experience with the Tinmith system, the user experienced fatigue and discomfort with holding the thumb markers up with an awkward pose [7] for extended periods of time. The range of the cursor movements is also limited by the available screen space, which affects the precision of the manipulation.

We previously introduced the *ultrasonic glove* input device and an initial exploration of distance-based interactions [8], including modeling by measurement gestures and affine transformations. In this paper, we present the full implementation of the interactions and multiple stages of evaluation of the techniques, as well as descriptions of the hardware. We also introduced a new interaction technique called the numeric entry technique utilizing the ultrasonic gloves.

Figure 1: Modeling by measurements using ultrasonic glove and filing cabinet (subfigures - a. width, b. length, and c. height)

The ultrasonic glove is built upon the original Tinmith pinch gloves [9], with the addition of a tilt sensor and a pair of ultrasonic transducers. In particular, we extend the Tinmith modeling UI for capturing dimensions which are orthogonal to each other and to the ground plane to support the many man-made objects that are orthogonal in nature. The ultrasonic transducers are mounted in the palm of the gloves and used to detect distance between the palms or from the palms to solid surfaces. The ultrasonic glove enables intuitive body gestures; an everyday example is when people describe measurements "I caught a fish *this* big" and place their hands at such distance apart. Our set of interaction techniques

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directly maps the reported distance to perform *modeling by measurements* (as illustrated in Figure 1:) and to support *affine transformation* interaction with virtual objects, and the aim of these interactions is to provide robust interaction techniques. The ultrasonic glove also supports a numeric entry technique for wearable AR system using natural body gestures. The original Tinmith marker-based glove technique is an example of an action at a distance interaction technique for wearable AR systems. *Our ultrasonic techniques offer the first within arms reach direct manipulation approach to modeling for wearable outdoor AR system.*

Following this introduction, Section 2 discusses previous investigations relating to glove-based input devices and ultrasonic sensors. In Section 3, we describe the distance-based techniques from our previous work and introduce the new numeric entry technique. Section 3 also describes the hardware implementation and the benefits of the ultrasonic gloves. Section 4 describes the user evaluations we conducted for our new techniques, including a pilot study, a formal user study, and an expert evaluation session. The paper ends with some discussion points and concluding remarks.

2 BACKGROUND

Glove based input devices attract a considerable effort from the research community. A survey of glove based input device by Sturman and Zeltzer [10] categorizes the approaches into technologies that track the position of the user's hand and technologies that determine the shapes of the user's hand. The survey highlights the benefits of glove-based devices as promoting the utilization of human bimanual dexterity for more natural interactions. There are two main forms of sensing for gloves. Firstly there are *pinch gloves* that sense when the tips of the fingers come in contact with thumb, i.e. a pinch gesture. The second form is a *data glove* that senses the joint angles of one or more of the user's fingers.

Historically data gloves have been used in AR/VR systems for direct manipulation tasks [10]. For example when a user reaches out and grasps a virtual cup, the system senses shape of the user's hand to determine the user's action. Dorfmuller-Ulhaas and Schmalstieg [11] investigated data glove-based manipulation input devices that tracks the joints of the user's index finger via a computer vision system sensing strategically placed ring and ball-shaped retroreflective markers on the user's hand. The positional data of the joints is combined with the kinetic models of the joints to allow gesture tracking of the finger to perform picking gesture on virtual objects. Wang and Popovic [12] take a vision-based approach to hand tracking with a pair of custom-patterned gloves. The camera interpolates the current hand pose from the unique pattern detected from the captured frame.

A common sensing technology for pinch glove input device is the incorporation of conductive fabric pads on the tips of each finger and thumbs into a pair of gloves [13]. Piekarski and Thomas [9] extended the pinch glove with an extra option in the palm for menu control. The pinching input events are mapped to a set of menu items to control the system, placed on the left and right bottom corners of the screen. A pair of fiducial markers is placed on the thumbs of the gloves to enable cursor-based interaction with the system. The chording glove by Rosenberg and Slater [14] is a text input device for wearable systems that mounts finger sensors on the fingers and various positions on the hand. The user presses on a combination of sensors to generate character based on a chording keymap.

Ultrasonic sensors have also been popular in interaction research. Fléty [15] employs an ultrasonic transmitter – receiver infrastructure to capture hand gesture. Fixed ultrasonic receivers are mounted above the user who wears gloves equipped with ultrasonic transmitters. The system is used for musical creation based on gestural interfaces. The tracking is completed using triangulation techniques, which can be autocalibrated based on an algorithm proposed by Duff and Muller [16]. Foxlin and Harrington [17] implement a similar system, called WearTrack, where the receivers are head mounted to track the position of a transmitters that are worn on the finger with two buttons. Ultrasonic sensors are also used in combination with inertial sensors in activity recognition by motion detection [18].

The combination of distance and tilt sensors in the ultrasonic glove is inspired by the HandSCAPE digital tape measure by Lee et al. [19]. HandSCAPE is a digital tape measure that is orientation-aware and used to create virtual models of physical objects based on direct measurements. HandSCAPE is employed for similar tasks of modeling by measurement, with examples such as box stacking optimization and modeling interior architecture.

3 DISTANCE-BASED INTERACTIONS

Our previous work described the two main categories of distance-based interactions: modeling by measurement and affine transformation. In this section we introduce a new interaction based on the ultrasonic gloves: the numeric entry technique. We also describe the hardware configuration and the benefits of the ultrasonic gloves in detail.

3.1 Previous techniques

Our previous work [8] introduced modelling by measurements and affine transformation techniques for the ultrasonic gloves. The user performs measuring gestures with the ultrasonic glove by extending the hands in different orientations to match with the dimensions of the physical objects. The distance data combined with the orientation of the gloves creates dimensions vectors to construct virtual models.

Affine transformation techniques map distance data to translation distances, scaling ratio, or rotational angle. By adjusting the distance between the hands, the user can translate, scale, and rotate virtual models, on the axis specified by the hand orientation.

3.2 Ultrasonic numeric entry technique

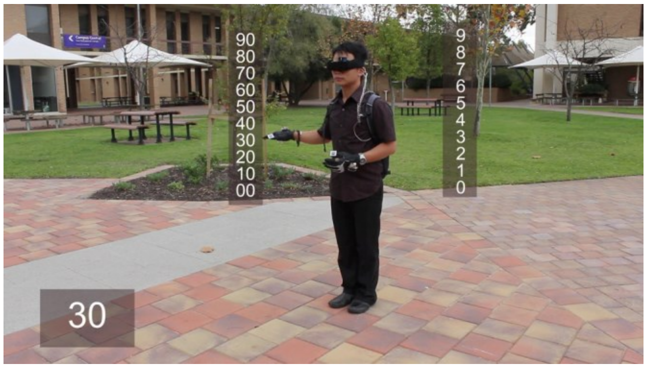

Figure 2: Ultrasonic numeric entry technique

The ultrasonic numeric entry technique employs the alternate use of the ultrasonic transducers with both hands. The ultrasonic numeric entry technique supports one-handed ranging operation by using the ground plane when the user adjusts the height of the hand with the palm facing down. We perform a mapping from the height of the palm to the set of digits from 0 to 9. If the hand is lower than a minimal height of 70 cm, which we determine is a comfortable low position for most adults to place their hand, the mapped digit will be 0. Every 5 cm increase that the user lifts their hand upwards is mapped to the next digit. For example, if the user's hand is within the range of 70 to 75 cm from the ground, the gesture generates the digit 1. Any height larger than (70 + 5 x 9 = 110) cm produces the digit 9, as well as height lower than 70 giving the digit 0. The values of minimum height (70 cm) and the increase threshold (5 cm) may be changed to suit different individuals. With this digit generation gesture, each hand will provide input mechanism for one digit of the amplification factor, with the non-dominant hand used for entering the *unit* digit*,* and the dominant hand for entering the *ten* digit*.* Figure 2: illustrates the ten digit selection process as performed by the user. Combining both digits from two hands allows the user to set the amplification factor to any values from the range of 1 to 99. The *amplification factor* is multiplied to the distance specified by the ultrasonic transducers being applied to the selected manipulation technique. Larger values can be achieved by allowing the dominant hand (ten digit) to rise higher to reach values of 10 or above. As the amplification factor increases, so does the granularity in precision of the operation. For example, with an amplification factor of 10 for translation task, for every centimeters of hand movement, the object is moved by 10 cm. With the ultrasonic numeric entry technique, the user is able to change the amplification factor to achieve the desired resolution of the interaction technique to suit various task scenarios.

3.3 Hardware

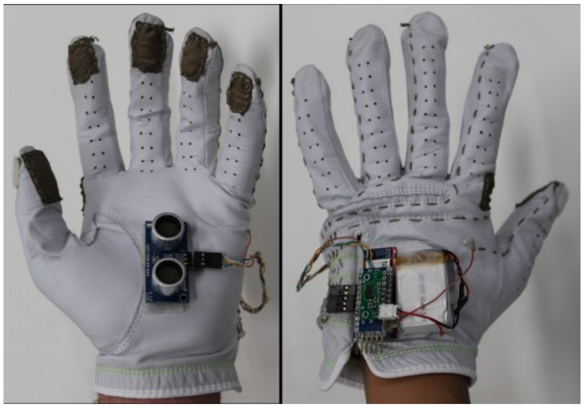

Figure 3: The ultrasonic glove

The ultrasonic gloves, as shown in Figure 3:, are built from off-the-shelf components that do not require any special skills to construct. At the heart of the glove is an Arduino Pro Mini microcontroller board[1], designed by SparkFun Electronics, clocking at 16 MHz. There are a number of versions of the Arduino board series, but the Pro Mini provides one of the smallest footprints at 1.77 x 3.30 cm. The Arduino Pro Mini board is connected to a Bluetooth Mate board, also made by SparkFun Electronics, to provide Bluetooth serial connections to the computer. The Arduino board has both analog and digital pins to support a range of companion boards. Three analog pins are connected to a 3-axis accelerometer breakout board, which is mounted parallel and on top of the Arduino board.

The Arduino board has several digital pins that can be configured both as input and output. One Arduino's digital pin is wired to a Parallax PING)))™ultrasonic board and acts as both an output pin for triggering the ultrasonic pulse and an input pin to read in the pulse width response. There is a pair of ultrasonic transducers on the Parallax board that has the distance range of 2cm to 3m. The Arduino, the Bluetooth Mate, and the accelerometer breakout boards are mounted in parallel layers and are attached to the back of a glove. The Parallax ultrasonic board is mounted to the palm of the glove. Conductive patches of fabrics are stitched to the finger pads of the glove using conductive threads, which run along the fingers towards the back of the glove, where the Arduino board is located. The thread from the thumb is connected to the ground pin on the Arduino board. The threads from the other four fingers and from the patch at the root of the index finger are connected to five digital input pins. The Arduino board has built-in pull up resistors, which set these five digital pins to high. A pinching gesture with the thumb to any of the five finger pads will pull the input to low, which is detected by the Arduino board and triggers an input event.

Communication with the glove is through a Bluetooth serial port. The Arduino board is configured to receive serial commands to start or stop the accelerometer and the ultrasonic transducers. Table 1 specifies the input and output serial communication of the glove.

Table 1. Types of data and the associated input (start/stop) and output serial data

Data	Start	Stop	Output
Accelerometer	A/a	P/p	"A,x,y,z" : accelerometer data in 3 axis.
Ultrasonic	R/r	Q/q	"R,x": x is distance in cm
Pinch glove	None	None	"Pk,x": k finger ID, x: pinch duration

We decided on the ultrasonic transducer as our distance sensor because it meets the size requirements to fit in the palm of the glove, as compared to laser rangefinder. We found a small size laser rangefinder board by Parallax[2], which we thought was slightly large in size, and but this device has a blind distance of 0 to 15 cm. As technology advances, we will be able to build future versions of the distance-based glove that will use more compact sensors with a larger range and better resolution. Our distance-based modeling and manipulation techniques will remain the same.

3.4 Benefits

The ultrasonic glove is a versatile input device that serves several purposes in a wearable AR system, including: modeling by measurements for physical objects and internal structures, affine transformation of translation, scale, and rotation, and numeric entry technique. Our new design complements the existing Tinmith interaction techniques with distance-based modeling and interaction techniques supported by the ultrasonic transducers. Often the development of new input devices leads to the replacement the existing solutions, but we chose the complementary approach to provide a wider choice of interaction techniques to the user for various task scenarios. By building on the existing glove-based input device, we leverage the intuitiveness and naturalness of the form factor, which is an established finding through the literature [13]. The hands-free nature of the device is also an advantage, especially for the outdoor settings. Recognizing these benefits of the existing pinch glove device was a strong design rational for our new glove.

Through our experience with the original pinch glove, the existing marker-based cursor control technique is known to cause fatigue due to the requirement to hold the marker within the view of the camera. Our distance-based interaction techniques rely on proprioception that does not require the user to maintain a visual concentration on the input device. Proprioception also allows the user to perform the tasks with natural hand gestures, thus reducing fatigue throughout the operation [20].

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[1] http://arduino.cc/it/Main/ArduinoBoardProMini

[2] http://www.parallax.com/portals/0/downloads/docs/prod/sens/28044-LaserRangeFinder-v1.0.pdf

The design of our distance-based interaction techniques is focused on being independent of other existing sensors in the AR systems, as to minimize sensor errors. Tinmith working plane technique [4] projects a virtual ray from the user's marker cursor into the AR world. As the virtual ray intersects with virtual objects, the user moves the onscreen cursor to change the position of the virtual object attached to the ray. The ray position is calculated based on the user position, which is reported by the GPS sensor. Therefore, the working plane technique is prone to errors caused by GPS jitter. Our ultrasonic modeling and manipulation techniques are not disturbed by the errors of any other existing sensors in the current system. For the errors within the sensors on our ultrasonic glove, we do not map the exact angular readings of the hand orientations to perform our techniques. Instead, we use the accelerometer as a tilt sensor to detect three different positions of the hands, which are less prone to sensor jitters and errors.

Our distance-based interaction techniques are designed to support precise operations. The ultrasonic transducers can report distance up to millimeter and centimeter resolution. By mapping the distance directly to modeling and manipulation tasks, we aim to give the user a familiar sense of real world precision. For the affine transformation techniques with the amplification factor of 1, there is a one-to-one direct mapping from the readings of the ultrasonic gloves to the AR system. The user can directly visualize the exact distance by which the virtual object is translated or scaled by observing the distance between their palms.

The common approach to designing an input device requires the indirect mapping from the *input domain* of the physical device to the *output domain* of the application, which are the two tuples in the "sixtuple" definition by Mackinlay et al. [21]. Examples include the mapping of the mouse movement on the mouse pad to cursors position on computer screen, or the mapping of knobs, sliders, wheels, etc. to various task domains. Such mappings require an active effort from the user in adapting their mental model of their actions on the input devices to the resulting effects in the AR system. For the ultrasonic gloves, distance in natural measurements is the common currency for the user, the input device, and the AR system. The user performs interaction gestures in natural distances (between the hands and other solid surfaces); the input device reports natural distance; and the AR system directly applies the natural distance to perform various functions. Our goal to provide a UI that minimizes the cognitive load during operation. Reducing cognitive efforts as well as lowering fatigue is outlined by Dunser et al. [22] as the guidelines to designing successful AR interface. The design of the ultrasonic gloves aims to achieve these two strategies.

4 EVALUATIONS

Throughout the development of the ultrasonic gloves and the interaction techniques, we have performed several evaluations in the form of a pilot study, user evaluation study, and a pilot evaluation with an expert user. In this section, we discuss the evaluations and how our findings have influenced the design process.

4.1 The OptiTrack Glove Pilot Study

The ultrasonic gloves are inspired by natural body relative measurement gestures that we often uses in our daily life. Before building the ultrasonic glove, we investigated the ideas of bringing these gestures to perform manipulation tasks. We built a mock-up version of the ultrasonic gloves using the OptiTrack indoor tracking system[3]. We mounted retroreflective markers on a pair of gloves that were tracked by the OptiTrack system. Within a reasonably sized tracking volume, we can track the tilt orientation and position of each glove with millimeter resolution. We subtracted the positions of the gloves to calculate their relative distance. We fed the distance and tilt orientation data to the system, which effectively was, the same exact information that the current ultrasonic gloves report to the AR system.

We recruited two participants to perform manipulation tasks with the OptiTrack gloves and the single glove for affine manipulations with the existing Tinmith marker technique. A pair of OptiTrack gloves was used for the affine transformation techniques involving the participant adjusting the distance between their hands, which was mapped to object's displacement, scaling ratio, or rotational angle. As previously described, the Tinmith employs a cursor control technique using ARToolkit marker. The user holds the marker in front of the head mounted camera, which is detected as a cursor on the user's screen. The user places the cursor on the virtual object and activates pinch glove commands to *translate, scale,* or *rotate* the virtual object. For each of the operation, the user slides the marker horizontally on the screen to adjust the position, scale, and orientation of the object. This operation is similar to using the cursor to adjust a virtual slider on the screen.

The aim of the pilot experiment is to obtain some initial feedback on the relative measurement gesture interaction concept. Therefore, we did not collect any quantitative performance data. Instead, we conducted information discussions, which provided insight into the final design of the gloves. Even though the OptiTrack system provides full 3D absolute positional tracking, we only required the relative distance between the hands and their tilt orientation to implement the techniques. This prompted us to augment the existing Tinmith pinch glove with a *linear distance sensor* and *a tilt orientation sensor.* From the discussion, the OptiTrack glove was favored in all but one task, when one participant preferred the marker-based technique for object translation. The comments supporting our new concept for a glove-based device included: "does not required to be in the field of view of the camera", "more comfortable", "accurate", and "intuitive". One participant suggested combining OptiTrack gloves with the existing eye cursor on the screen, which inspired the *relative translation* technique. The other participant expressed their tendency to perform bimanual operations with the OptiTrack gloves, which lead us to investigate the *ultrasonic numeric entry* technique. Based on the approving feedback, we started designing and implementing the ultrasonic glove input device.

4.2 User evaluation of modeling by measurement techniques

We conducted a formal user study to evaluate the modeling by measurement technique using the ultrasonic gloves.

4.2.1 Design

Our hypotheses are as follows:

H1: The ultrasonic technique is measurably faster in time to complete the task over the marker technique.

H2: The ultrasonic technique is measureably more accurate in smaller measurement modeling errors over the marker technique.

H3: The ultrasonic technique has a measureable preference by the participants .

We designed an experiment to compare the ultrasonic modeling techniques to the existing Tinmith marker-based technique. The base task is to create a virtual box-shaped object by capturing the three dimensions of width, length, and height from the physical environment. We set up three types of modeling tasks: A) modeling an *area task*, B) *physical object task*, and C) a shoulder-high object

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[3] http://www.naturalpoint.com/optitrack/

height task. For the area task, we asked the participants to create a virtual 3D rectangular to fit an outdoor area with the dimensions of 1.43 (X) x 2.18 (Y) x 0.70 (Z) m, as shown in Figure 4:. For the physical object task, we used a cardboard box (to emulate an outdoor bin) with the dimensions of 0.41 (X) x 0.41 (Y) x 0.63 (Z) m, shown in Figure 5:. For the height task, we asked the participants to capture the height of a branch of a tree at 1.47 m high. The height task was intended to evaluate the body relative nature of the ultrasonic glove. The combination of three modeling tasks (A, B, and C) with two techniques (ultrasonic U, and marker M) create six tasks (UA, UB, UC, MA, MB, and MC). Each participant performed one training iteration and then one data collection iteration (with random order of the six tasks). For each task, we collected the time to complete the task as well as the resulting dimensions of the object. The errors in dimensions are calculated from the measurements of the physical area/objects before the study started. After the six tasks, the participant completed a questionnaire about their preferences for either of the two techniques. The questionnaire asked the participants about how easy it is to understand, how logical the modeling process is, and how intuitive each technique is. The questions were presented in a visual analog scale, in which the participant indicated with a pen stroke on a continuous line the scale of their responses, from *Easy* to *Hard, Logical* to *Make no sense,* and *Intuitive* to *Complicated*, respectively. The questionnaire also asked the participants to rank their preference between the two techniques, and to provide explanations.

Figure 4: The outdoor area for virtual modeling task

4.2.2 Experiment

We recruited 14 participants, all male aged 20 to 45 years (mean 28.8, SD 7.7). The participants were asked to wear the Tinmith backpack computer to perform modeling tasks using two modeling processes: one using the original marker-based Tinmith technique and one using the ultrasonic gloves.

For the marker-based technique for all three tasks (A, B, and C), the participant is required to step directly to the physical area or object to place a virtual unit cube. The participant moves backward to gain a vantage overview of the modeling area/object, from which they perform scaling operation. The participant holds the thumb marker in front of the head mounted camera. An onscreen cursor is overlaid upon the marker. The participant selects the virtual box with the marker and slides the cursor left and right to adjust the size of the virtual box, one dimension (X, Y, Z) at a time. Switching dimension is enabled with the pinch menu. For the ultrasonic technique, the participant performs modeling by measurement technique as previously described in Section 3.1 and shown in Figure 1:, for modeling task B of the physical box. For the modeling task A of the outdoor area, the participants faced the ultrasonic glove towards the walls (marked with the red and blue arrows in Figure 4:) and the ground plane to capture the measurements. The outdoor area modeling is an example of modeling tasks with dimensions larger than the participants' arm stretch. For task C, the participants faced the ultrasonic transducers towards the ground and raised their hand to match to the height of an outdoor tree at 1.47m tall.

4.2.3 Results

We performed a pairwise t-Test between the ultrasonic and the marker techniques for each of the types of modeling tasks (A, B, and C), on the time and error data. Before the study, we measured the dimensions of the physical area and the box. The error data was calculated by the absolute difference between the pre-measurements and the dimensions of the virtual object the participants created. There are three sets of error data for three dimensions. We multiplied the dimensions to create a fourth set of *volume* error data, which was calculated as the difference between the *volumes* of the area and the box and the *volumes* of the virtual object. Overall, we performed pairwise t-Test on one set of time data, and four sets of error data (volume, X, Y, and Z). We first performed the t-Test on the volume data with an alpha value of $\alpha < 0.05$, and three post-hoc t-Tests on the error X, Y, and Z data with a Bonferroni correction with $\alpha < 0.0167$. Task C, the height task, required only the Z error data to be analysis, and an alpha value of $\alpha < 0.05$ was employed.

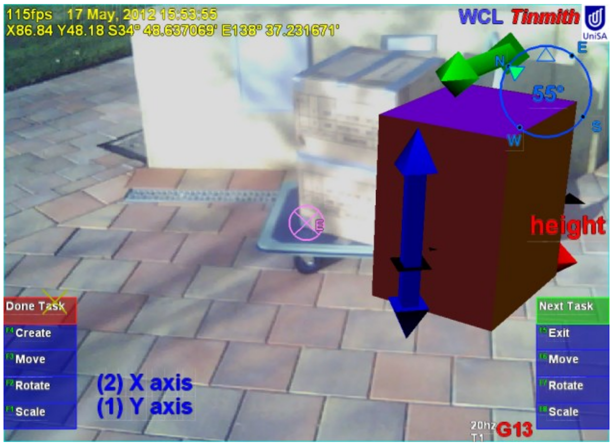

Figure 5: Example of Task B of modeling a physical box

Modeling task A of physical area

There was a significant effect ($p < 0.05$) for the time to complete the tasks between the ultrasonic (mean 47.7s, SD 14.2s) and the marker (mean 154.1s, SD 64.5s) technique to *support H1 that the ultrasonic has a measureable advantage in time to complete the task.* Additionally the ultrasonic technique displayed a consistent performance across participants, as shown by the lower SD.

There was no significant effect ($p = 0.06 >= 0.05$) for the volume error data between the ultrasonic (mean 0.82m^3, SD: 0.69m^3) and the marker (mean: 2.88m^3, SD 4.54m^3). Therefore, H2 was rejected for the volume data.

There were significant effects ($p < 0.0167$) for the error in the X (depth dimension from the participants' viewpoint) between the ultrasonic (mean 0.45m, SD 0.37m) and the marker (mean 0.91m, SD 0.37m) techniques that *H2 was supported for the depth dimension*. There was no significant effect ($p >= 0.0167$) for the two (Y and Z) error data; therefore, H2 is rejected in these dimensions.

	Time						ErrorX				ErrorY			
	Virtual		Actual		Height		Virtual		Actual		Virtual		Actual	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ultrasonic	47.73	14.20	40.87	16.80	17.38	6.60	0.46	0.37	0.06	0.10	0.39	0.42	0.18	0.24
Marker	154.09	64.50	98.45	71.40	65.16	40.80	0.92	0.37	0.74	0.53	0.50	0.33	0.60	0.55

Table 2. Time (sec) and error data in X and Y (m)

	ErrorZ						Volume errors					
	Virtual		Actual		Height		Virtual		Actual		Height	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ultrasonic	0.24	0.20	0.11	0.10	0.16	0.26	0.82	0.69	0.06	0.08	0.14	0.21
Marker	0.46	0.51	0.39	0.24	0.50	0.91	2.88	4.54	1.39	2.08	0.60	0.87

Table 3. Error data in Z dimension (m) and volume errors (m^3)

Modeling task B of physical object

There was a significant effect ($p < 0.05$) for the time to complete the task between the ultrasonic (mean 40.8s, SD 16.8s) and the marker (mean 98.4s, SD 71.3s) to support *H1 that the ultrasonic technique has faster completion time*. Once again the mean time for completion is much more consistent when the ultrasonic gloves are employed.

There was a significant effect ($p < 0.05$) for the volume error data between the ultrasonic (mean $0.06m^3$, SD $0.07m^3$) and the marker (mean $1.39m^3$, SD $2.09m^3$) techniques to support H2.

There were significant effects ($p < 0.0167$) for the three dimensions (X, Y, and Z) error data between the ultrasonic and the marker techniques. Table 1 and 2 provide a summary for mean and SD values the different dimension data. We can state that *H2 was fully supported in all three dimensions.*

Modeling task C of height

There was a significant effect ($p < 0.05$) for the time to complete the task between the ultrasonic (mean 17.3s, SD 6.5s) and the marker (mean 65.1s, SD 40.7s) techniques to *support H1*.

There was no significant effect for the error in Z dimension between the ultrasonic (mean 0.16m, SD 0.26) and the marker (mean 0.5m, SD 0.91m) techniques for these tasks. Therefore, H2 was rejected.

Questionnaire

We converted the visual analog responses in the questionnaires into percentages by physical measurement of the location of the participant's hand written mark. An analysis by Dexter and Chestnut [23] concluded that t-test and ANOVA are good statistical analysis tests for continuous and discrete visual analog scale data. We performed pairwise t-Test on the percentage values between the ultrasonic and the marker techniques for each of the question. There were significant effects ($p < 0.05$) across all questions that *the ultrasonic technique supports an easier to understand and more logical modeling process, as well as being more intuitive to use.* Figure 6: depicts the preference data from the questionnaire. When asked to rank the two techniques, 100% of the participants ranked the ultrasonic technique over the marker-based technique. The reasons ranged from "being more comfortable", "more stable (than the GPS error experienced by the marker", and "more intuitive". The analysis of the questionnaire supported H3 that *the ultrasonic has a measureable preference by the participants.*

4.3 Expert user and manipulation technique

One of the benefits of the ultrasonic glove is the ability to accommodate existing techniques. We performed a task-based evaluation experiment with one expert user to utilize the ultrasonic gloves, the AR marker-based technique, and a trackball for manipulation tasks. The ultrasonic glove performed the affine transformation techniques via adjustments of the distance between the hands. Both the marker and the trackball were used for controlling an onscreen cursor to perform affine transformations of virtual objects.

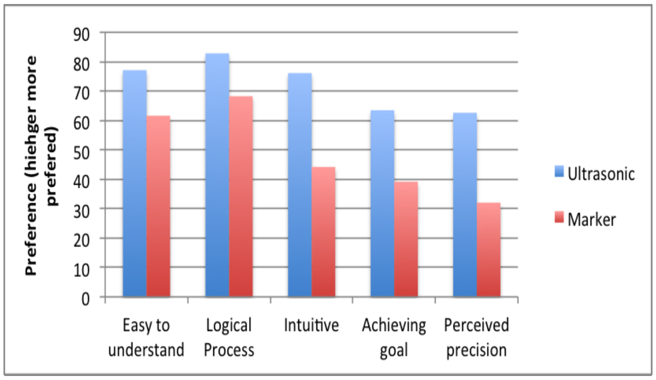

Figure 6: Preference data from questionnaire

Throughout the experiment, the user wore the same pair of ultrasonic gloves, even when using the trackball. There were three tasks, namely translation, rotation, and scale. For each task, two virtual unit boxes were placed at 20 m distance from the user, and one of which was randomly translated, rotated, or scaled by a certain displacement. The user was required to perform affine transformation on the other box to match the position, orientation, and size between the two boxes. Three techniques (ultrasonic gloves, marker-based, and trackball) and three affine operations (translation, rotation, and scaling) made nine tasks per iteration. We randomized the order of the tasks so that the user is required to switch randomly between three input mechanisms. We collected the time to complete the tasks and the resulting position, orientation, and size of the boxes to calculate their difference, which was the error data for the user's operations. The expert user completed seven iterations. We performed a one-way ANOVA analysis on the data and found no significant difference between the three techniques in all tasks. The ultrasonic glove is also able to accommodate existing techniques on the same input device, namely the glove. As the modeling by measurement is additional technique and the ultrasonic an additional sensor, we believe the choice of input technique should be left the user. Our techniques become an additional tool in the user's UI toolbox, and as such must complement and not interfere with the existing techniques.

4.4 Overall results

The evaluation demonstrated that the ultrasonic techniques offer several advantage over the existing marker-based technique. One of the main advantages is the time to complete the task. As can be seen from the study results, the ultrasonic techniques reduce the overall time up to four times as compared to the marker-based technique. The result is an indication of the difference in the nature of the two techniques: the marker-based technique is based on the action at a distance, while the ultrasonic technique employs a direct manipulation approach.

During the modeling study, we noticed that the participants had difficulty modeling the physical box with the marker technique. We believe a contributing factor was caused by the virtual model obscuring the physical box during the modeling process. The obscurement reduced the participants' ability to match up the edges of the virtual model with those of the physical box. This observation explained the measureable effects in all dimensions between the ultrasonic and the marker techniques. The outdoor area did not suffer from such phenomenon. The edges of the outdoor area were defined by the walls and a bench, which are not obscured by the virtual model that the participants' were manipulating. Therefore, there was only a significant effect in one of the dimension in the result analysis. The dimension that showed significant difference is dimension of the virtual object that is parallel to the normal axis of the user's image plane. This is one of the main drawbacks of the marker-based technique.

The evaluation indicated that the ultrasonic glove is a versatile input device that supports distance-based modeling. The modeling by measurement techniques offer an improvement over the existing marker-based modeling technique for outdoor AR, both in time to complete the task as well as reducing modeling errors in some cases. The ultrasonic glove also supports manipulation technique, with equivalent performances to the existing marker-based technique. Moreover, the distance-based modeling and interaction techniques can be generalized to different sensor technologies, indoors or outdoors, such as the OptiTrack system, or using a Kinect, which accommodate for future advancement of sensor technologies.

4.5 Limitations and Future Work

There are many environmental factors affecting the accuracy of the ultrasonic transducers, including ambient temperature, air turbulence, humidity, and target size [24]. The error variation per one degree Celsius, for example, is 0.1%. Distance calculation is performed on the microcontroller board, instead of on the AR system. At the moment, we have not implemented hardware temperature or any other environmental sensors to account for the variations. Therefore, when there is a considerable change in the aforementioned elements of the environment, we are required to modify the hardware code for the Arduino board to adapt to the changes.

The ultrasonic gloves operate mainly within the personal area surrounding the users. There is an upper limit to the specified distance imposed by the user's arm length. The techniques are most naturally suitable for body sized objects. For larger objects such as outdoor buildings, we implement the *amplification factor* to magnify the effective distances, at the compromise of granularity and increased cognitive overhead for the user. We face technological challenges in performing simultaneous actions with the pairs of transducers on both hands, due to the interference from the ultrasonic reflection off the ground. We are still investigating the usage of transducers with different ultrasound frequencies. We implemented a solution that allows the user to automatically switch between the transducers on both hands by facing the palm down one at a time, without having to manually switch through pinch glove commands.

Figure 7: Concept diagram of the curvature capture technique

We also wish to explore the usage of the ultrasonic gloves to model the curvature of outdoor building. Wither et al. [24] employ a laser rangefinder to determine the orientation of a vertical planar surface by swiping the rangefinder along the surface. In a similar approach, the user of the ultrasonic gloves faces the palm towards a curved surface at a fixed distance from the body and walk along the surface in a straight line. A concept diagram is shown in Figure 7:. Throughout the walk the ultrasonic transducers reports the distance between the user's (palm) and the wall. For a straight wall, the distance would remain constant; however when the wall is curved, the distance fluctuates. By capturing the fluctuation of the distance data, we can reconstruct the curvature of the wall, assuming that the user walks on a straight line parallel to the cord of the curved wall. We have implemented an initial version of this technique, but more investigations are required.

5 CONCLUSION

We presented the distance-based interactions using a new input device called the ultrasonic glove. The ultrasonic glove is based on the original pinch glove for virtual reality systems, with the additions of a linear distance ranger and a tilt orientation sensor. A pair of ultrasonic transducer is placed in the palm of the glove as a distance sensor. The ultrasonic glove supports intuitive and natural direct manipulation technique of modeling by measurements by *feeling* the dimensions with body gestures. The ultrasonic glove supports affine manipulation techniques in which the user adjusts the distance between the hands to perform translation, scale, and rotation of virtual objects. Our ultrasonic glove also enables a numeric entry mechanism for wearable AR systems by a hand raising gesture. Our interaction techniques are generalizable to different sensor technologies. The ultrasonic glove is only one example implementation for our distance-based interaction techniques. Our techniques can be implemented using different technologies, such as the OptiTrack system, or using a Kinect, which we have yet to fully explore. In the future, we wish to expand the distance-based interaction techniques for more tasks, including modeling the curvature of outdoor buildings and objects.

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