Embodied Axes: Tangible, Actuated Interaction for 3D Augmented Reality Data Spaces

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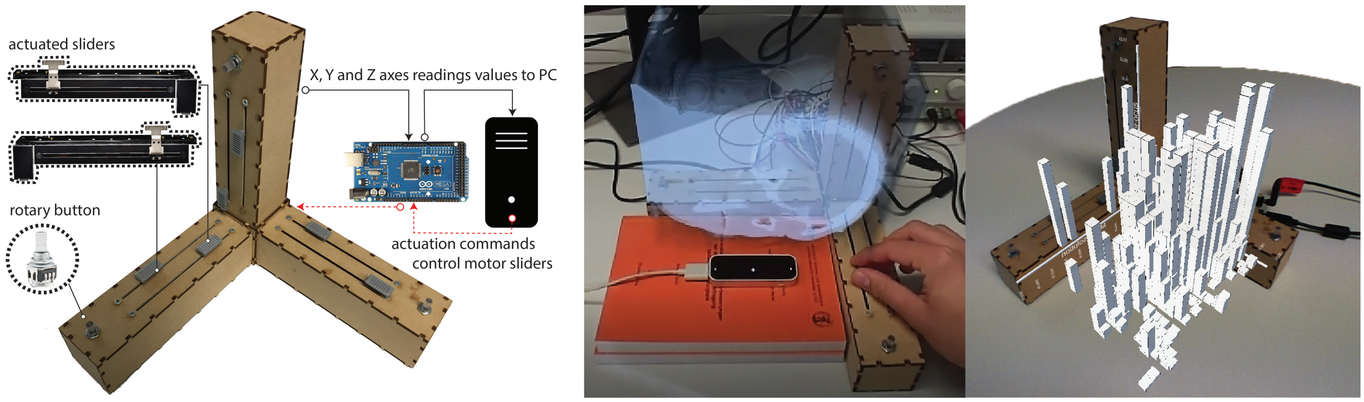

Figure 1: Embodied Axes is built with *off the shelf* electronics components which comprise of actuated linear potentiometers and rotary buttons. A serial communication sends the sensors' values to the computer, and read commands from the computer to move the sliders to given positions. An AR headset displays *in place* an immersive 3D visualisation inside the 3D space of the Embodied Axes. These views are captured from the point of view of a Meta 2 headset.

ABSTRACT

We present Embodied Axes, a controller which supports selection operations for 3D imagery and data visualisations in Augmented Reality. The device is an embodied representation of a 3D data space – each of its three orthogonal arms corresponds to a data axis or domain specific frame of reference. Each axis is composed of a pair of tangible, actuated range sliders for precise data selection, and rotary encoding knobs for additional parameter tuning or menu navigation. The motor actuated sliders support alignment to positions of significant values within the data, or coordination with other input: e.g., mid-air gestures in the data space, touch gestures on the surface below the data, or another Embodied Axes device supporting multi-user scenarios. We conducted expert enquiries in medical imaging which provided formative feedback on domain tasks and refinements to the design. Additionally, a controlled user study was performed and found that the Embodied Axes was overall more accurate than conventional tracked controllers for selection tasks.

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3D Visualisation, Device, Actuation, Tangible Interaction, Augmented Reality

CCS Concepts

•**Human-centered computing** → **Human computer interaction (HCI);** *Haptic devices;* User studies; Please use the 2012 Classifiers and see this link to embed them in the text: `https://dl.acm.org/ccs/ccs_flat.cfm`

INTRODUCTION

The inherent flatness of screens and printed media has led to widespread application of 2D visualisation techniques for viewing slices or cross-sectional areas of 3D volumes in medical imaging, geology and engineering, to name just a few domains. When data has no inherent spatialisation (e.g., quantitative and qualitative data sets involving many dimensions) it is sometimes helpful to visualise these data in 3D—such as in the case of 3D scatterplots to explore correlations and clusters across three dimensions or space-time cubes for spatio-temporal data [1]—and explore these volumes using projections and cross sections (e.g., a time slice across multidimensional time-series data). However, immersive Augmented and Virtual Reality (AR/VR) offers the capability to provide true stereo rendering and stable positioning of such a data representation so that the user can physically peer around occlusions in the data and perform interactions (such as selection) by directly manipulating the data.

Selection is a fundamental task in visualisation [18] and helps users to: obtain details of a particular region or data point; zoom into a region; or extract a range of data (similar to a range query or filtering operation). While selection has been extensively studied on 2D interfaces, selections in immersive environments remain challenging. Standard interactions available with common types of headsets require mid-air gestures with hands or tracked controller devices in a way that is problematic for standard visualisation tasks. This is because mid-air gestures offer little support for precise selection in visualisation and may be fatiguing and imprecise [19]. This poses two specific challenges our work is aiming to address: (C1) to enable precise interactions for selection in 3D visualisations; and (C2) to coordinate interaction and visual feedback through direct manipulation such that the user can have a better understanding of interactions and affordances. Traditionally, one has to chose between these goals: tangible controllers that provide precise selection (C1) typically give visual feedback on a separate screen [17, 40, 44], while direct manipulation (C2) was done with direct, but imprecise, mid-air devices [3, 33].

In this paper, we present *Embodied Axes*, a visualisation environment for making precise (C1) and direct (C2) selections in 3D visualisations. Embodied Axes consists of three orthogonal tangible and actuated sliders with an augmented reality head-mounted display that aligns a 3-dimensional visualisations "inside" the space spanned by the three sliders (Figure 1). The device is an embodied [12] representation of a 3D data space—each of its three orthogonal arms corresponds to a data axis or domain specific frame of reference. Each axis is composed of tangible, actuated range sliders for precise data selection, and rotary encoding knobs for additional parameter tuning or menu navigation. The resulting device is relatively simple, low-cost, and could conceivably be deployed on the desk of a medical practitioner, engineer or other professional who depends on data visualisation or imagery. To the best of our knowledge, no work on tangible AR has directly addressed both challenges at the same time.

We conducted a qualitative study with three medical domain experts to fine-tune our design and inform valid tasks for a controlled user study. We then conducted a controlled user study with 12 participants evaluating speed and precision of 3D selection tasks using the device versus the use of standard tracked controllers. Our results indicate that the Embodied Axes is more accurate and faster for single value selections, and more precise for 3D selection compared to tracked 3D VR controllers.

RELATED WORK

Three-dimensional representations that accurately depict spatial data have obvious application in medical imaging, engineering, and flow visualizations. However, they have also been explored for quantitative data using 3D-scatterplots [31, 13], 3D multi-dimensional scaling [31], and space-time cubes [1]. Space-time cubes—which maps the third spatial axis to time—are popular for geotemporal visualization [6, 27, 26], as well as for dynamic networks [2], videos [14], and multi-dimensional data [42]. In all these cases, understanding is tightly coupled to correct interpretation of spatial relationships including distances between points or features, shapes of clusters, and orientations. This includes generic operations [1] such as value selection, defining ranges along each dimension, selecting specific elements in each combination of dimensions, defining cutting planes, selecting points and shapes in space, or magnifying the space through lenses [10].

In this work, we consider a tight integration of visualisation space and interaction space to improve exploration and navigation through selections, following the spatio-data coordination principles outlined by Cordeil *et al.* [8]. Their design space included several very early prototype devices coupling interaction space to data, including a device with axis sliders. This device was only mentioned in passing and no design detail or evaluation was provided. Our research provides the full realisation and design for an evolution of such a device, with enriched feedback using actuation, as well as a thorough evaluation and comparison to conventional techniques for selection tasks.

This section overviews interaction techniques for data visualisation in immersive environments, tangible interfaces and actuated interaction for a richer and multimodal representation of data.

Interaction with 3-dimensional data

In all of the imaging and visualisation applications considered above, interaction is essential, to allow users to select regions of interest and zoom-in or otherwise navigate and explore the data. Most interaction techniques and devices have been designed for 2D screen displays. For example, medical imaging with (software) slider controls to adjust cutting planes. Here, users mainly interact single handed using an indirect interaction device like a mouse or trackball. However, emerging mixed-reality display devices have proven superior for perception in several tasks, especially when exploring complex shapes [3]. Moreover, emerging mixed-reality displays allow for direct manipulation with the virtual content in space, e.g., selecting points and placing cutting planes [3]. Most commonly, these operations are performed through free mid-air interaction where users perform interactions without any physical support, while controllers—e.g., as in the case of the HTC Vive, touch surface [37], paper [38], or even rubber ball [21]—are often used for precision and visual feedback. Still, mid-air interaction suffers from fatigue due to arm movements and reduced precision due to unintended body movements, tremor, and fatigue. Consequently, a range of tangible interfaces and controllers that are fixed in space [24] have been designed to alleviate these drawbacks.

Tangible User Interfaces

Tangible user interfaces (TUIs) use physical artifacts for interaction [15], many of which have been designed to support navigation and selection in 3D visualization [23, 8]. Benefits of TUIs have been found in particular when performing tasks eyes-free [24, 29]. They benefit memorisation, proprioperception, and have been found enjoyable [39].

Some TUIs conceptually extend the mouse in that they allow for basic navigational input, e.g. camera rotation or menu selection [44, 34, 41, 36, 11]. Other approaches provide tangible sliders or rotators to allow for value selection on axes [40]. Again, other approaches build tangible representations of the 3D space. For example, the TouchCube [44] is a cube input device with touch-sensitive faces and edges. Rotations are performed with drag interactions on opposite faces. Similar, Rubikon [35] implements interactions on a rotatable Rubix cube, including discrete rotation in 3D environments. Other cube-shaped devices have been used for navigation menus and setting state variables [34]. CubicMouse [17] allows for selection inside a 3D volume through movable rods and buttons mounted to the device. Sousa et al. [37] designed touch-based interactions for VR exploration and selection of 3D slices of CT volume scan data. Lopes et al. [30] developed a VR system for exploring CT colonography data in 3D using mid-air interactions to navigate and view the detailed CT slices.

While accounting for stable and precise interaction, these devices do not include any *direct* visualization overlaid over the device, leaving a discrepancy between the interaction and visualization space [3, 8]. CAPTIVE [7] is an example of such a device, being an AR system that consists of a cube wireframe and a pointing device. While the wireframe is used to track rotation and absolute position of the visualization, the pointing device is used to point to positions inside the wireframe.

Our technique is a novel tangible UI in that it embodies only the spatial dimensions (axes), each bearing a set of actuated sliders for simple and range selection. These physical axes span a 3-dimensional space in which any data visualization can be projected using mixed reality. Moreover, this leaves space for additional interaction modalities with controllers, physical cutting planes, and simple mid-air interaction.

Actuated Interaction

Actuated interaction refers to feedback given through a tangible controller. For example, inFORCE [32] is a pin-based shape display that acts both as input and haptic display. The authors describe a series of use cases that include visualisation of geoscience data (earth layers), and a medical application rendering the pulse of a patient for medical training. However, such an interface which renders only a surface cannot cope with complex data visualisations such as scatterplots (bars cannot depict points above one another) or dense visualisations such as medical images or certain space-time cubes.

In virtual reality, recent research has used actuation to provide haptic feedback on 6DOF tracked controllers for data visualisation. Vibration feedback was given on the density of clusters while the controller is moved through a virtual scatterplot and found to improve 3D scatterplot density estimation [33]. The actuated sliders in our Embodied Axes device also afford the capability to provide haptic feedback about data, as described in our Design section.

Data Physicalisation

In recent years, advances in computer aided manufacturing (such as low-cost 3D printing) has led many data visualisation researchers, engineers, and artists to consider the possibilities of creating physical manifestations of data, known as data physicalisation [25]. Data physicalisation could be considered something of an ideal for data representation in terms of its ability to engage people through senses beyond vision [43]. However, this ideal is limited by current technology to either static representation or large, expensive and cumbersome implementations of dynamic physicalisations [16]. Our work attempts a practical compromise, physicalising the dimensions of the data rather than the data itself, in a way that supports concrete interactive tasks through tangible feedback, with a fully dynamic AR data display. The resultant device is relatively simple, low-cost and could conceivably be deployed on the desk of a medical practitioner, engineer or other professional who depends on data visualisation or imagery.

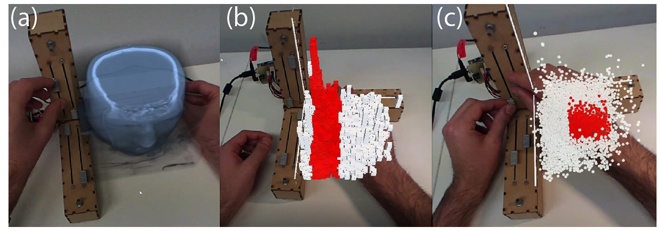

Figure 2: (a) 1D slice selection, (b) 2D range selection, and (c) 3D (bounding box) selection. Screenshots taken from Meta 2 headset.

EMBODIED AXES: DESIGN

Embodied Axes physically embodies a three-dimensional data visualisation space (Figure 2). The device is designed to allow users to make selections in this 3D data space (whether the data be multivariate quantitative and qualitative, medical, engineering or scientific visualisations, space-time cubes, etc.) with high precision. The device consists of three orthogonal solid axes, each representing one of the dimensions of the 3-dimensional Euclidean space, usually referred to as `x`, `y`, and `z`. All axes are the same length, to encompass a data volume of approximately 10*cm* on a side. Each axis features two parallel actuated sliders and a rotating knob (which also serves as a push button) mounted at the far end of each axis (Figure 3). The two parallel sliders per axis allow settings for *min* and *max* values for each axes.

Hardware Design

Figure 1 highlights the physical components of Embodied Axes. The device is made up of three orthogonal axes, each of which have two motorised linear potentiometers and one rotary encoder. The potentiometers have an operating range of 100mm with a variable resistance (0-10k ohms) reading to indicate the physical position of the slider knob. The resistance value is measured using a voltage divider circuit connected to an ADC port on an Arduino Mega providing a range between 0 and 1023 to indicate the current physical position of the slider knob.

The linear potentiometers are also equipped with a small DC motor to provide control of the sliders' knob position. Each DC motor is connected to a common H-bridge integrated circuit that is also connected to the Arduino Mega. This allows the direction and speed of the DC motor to be computer

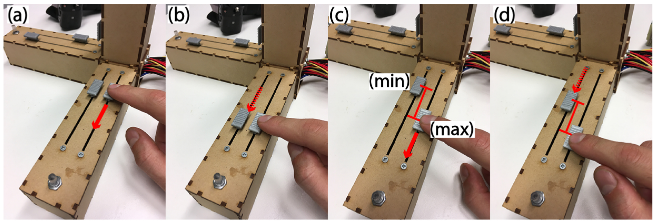

Figure 3: Simple slider interaction (a,b) and range sliding interaction (c,d) using motorised actuation.

controlled. Pulse Width Modulation is used to provide speed control of the DC motor to allow more precise position control. We employed an Arduino Mega 2560 to control the electronic components. This provides sufficient I/O pins to control three axes with one microcontroller. The electronic components are incorporated into a custom Arduino shield that can be plugged into an Arduino Mega. The shield provides control of six H-bridge circuits for controlling the DC motors, 6 Analogue to Digital ports to measure potentiometer value (slider knob position) and three I/O ports to capture the rotary encoder position. Plugs to each axis were added to the shield supporting easy assembly. The physical design and construction of the axis were designed in Autodesk inventor and cut from 3mm MDF with an Epilog Laser cutter.

Software Design

As per Figure 1, at a high level the Arduino program reads the slider resistance value (between 0 and 1023) and the rotary and push actions of the rotary knob and sends those values to a PC via serial COM port. The Arduino main loop also reads messages from PC via COM port, to drive the DC motors in order to snap knobs to a given position or to encode force feedback on a certain range for haptic feedback. We designed a simple C# API compiled into a DLL to establish the serial connection between the Arduino and the PC, to read and send messages. The PC library to control the Embodied Axes contains four basic functions – `moveTo` (moves the slider to a position), `follow` (follows another slider), `fillHaptic` (renders continuous force feedback on the axis), `fillHapticSteps` (renders regular discrete notches along the axis). The DLL is imported into a Unity program which can: consume slider positions, rotary knob deltas and button push events; and, control actuation of sliders (Figure 1).

Operations and Interactions

The actuated motors can be used to design typical slider and range slider widget-style interactions, or provide haptic feedback to encode data values along an axis (summarized in Figure 3). The motors attached to the actuated sliders can be programmed to encode different levels of force feedback. We developed functions to map discrete notches along the axes as in [29]. This function can be used to provide haptic feedback when a user scrolls a discrete variable along an axis—i.e. the user feels a notch every time they scroll through a value. This function can also be used to encode force feedback on a data distribution. For example it is possible to map data values to the resistance of the motor. In that case when the user scrolls through a variable along the axis, it is possible to feel proportional resistance to the data values (e.g. high values will involve higher force feedback).

For each axis, a user of the device can independently set:

- **single values** using the position of either slider. Enabling the `follow`-function with a range set to 0 snaps both knobs at the same value and turns the axis into a simple slider.
- **range values** using the position of both sliders on the same axis.
- **fixed-range values** The `follow` function can set a range (0 to 100mm) between the two knobs. By moving the min or the max knob, the other knob `follows` and preserves the specified separation, which results in a fixed-range-sliding interaction.
- **delta rotation values** using the rotating knob. The rotary buttons can be used to widen or shrink the range of range slider. They can also be used to set the precision of the slider (steps) as explained in the following.

Individually or in combination, these basic interactions allow for a range of operations in the 3D visualisation space. To describe our operations, we introduce the following notation: $(X,Y,Z) \in D$ describes the three dimensions; X' means that a single value is selected on the X dimension; X'' means a range selection (two values) are selected on the X dimension. A dimension without any value specified is written as X. We can express the system in any state as a tuple of all three dimensions; for example the tuple $S = (X'', Y', Z)$ expresses a range selection on the X dimension, and single value selected on the Y dimension (two values), and no value specified on Z. For the sake of explaining operations in this section, we consider X,Y,Z as mutable and we write dimensions in their order of selection, starting with the dimension with the most values selected. We can now specify all ten possible operations with combinations as described above. In the following, we focus on the most prominent operations in visualisation and that we implemented for demonstration, expert evaluation and controlled user study.

- **No selection** (X,Y,Z)**:** no selection in the visualisation.
- **simple slice selection** (X',Y,Z)**:** a slice selection selects a single slice in a 3D visualisation along any axis. With Embodied Axes, we can use a single slider in any of the axes to create a slice selection (Figure 2 (a)). Slice selections are of interest in space-time cube systems [2, 6] or CT scan volume data when searching for slices with specific properties or visual patterns.
- **Point selection** (X',Y',Z')**:** three slice selections on each axis defines a point selection.
- **Range selection** (X'',Y,Z)**:** a range selection is similar to a slice selection. (Figure 2 (b))
- **Bounding box** (X'',Y'',Z'')**:** three range selections on each axes define a 3D bounding box selection (Figure 2 (c)).

Integration with Mixed Reality Displays

During the design of Embodied Axes, we went through four prototype stages, experimenting with different hardware and AR/VR head mounted displays. This section gives an overview over our design iteration and lessons we learned while designing Embodied Axes.

Prototype #1: Low-fi video pass-through–In our first prototype, we mounted a Leap Motion[1] controller onto the HTC Vive VR headset and used the video pass-through from the Leap Motion infrared cameras. The user could only see in gray scale but was able to view the Embodied Axes and able to control the sliders and the rotary push buttons. This setup allowed us to explore how to overlay UI components on top of the Embodied Axes and to visualise a cube volume inside the 3 axes.

Prototype #2: Tether-less immersive Augmented Reality–We integrated the Embodied Axes with the Microsoft HoloLens immersive augmented reality headset. This version of the setup offered a less constrained environment for the user and could display stereo graphics anchored in the environment. The Embodied Axes controller was connected to a desktop computer to communicate slider locations and button states to the HoloLens headset via WiFi network at a very low latency. While this setup was promising in terms of usability and stability of the visualisation, the HoloLens' limitations in field of view (35 degrees) and graphics capabilities (resolution 1268x720) were found insufficient for actual applications.

Prototype #3: Tethered immersive augmented reality with motor actuation and finger tracking–We used the Meta 2 see-through immersive augmented reality headset to display the immersive visualisation. The Meta 2 provided a bigger field of view (90 degrees) and a higher resolution (2560 x 1440) than the HoloLens, making the system more usable and suitable for visualisation tasks. Additionally, we redesigned the hardware board by creating a PCB (see section 3) for more robust readings of sliding and rotary values and also for easier motors actuation. In this version of the prototype we investigated how the immersive Embodied Axes setup could be used in combination with mid-air gestures. We placed a Leap Motion controller at the base of the Embodied Axes to track hand movements and coordinate selection coordinates with the actuated sliders (see next section, Figure 4). **Prototype #4: HD colored stereo video passthrough**–The last prototype used an RGB stereo pass through augmented reality with the stereo ZedMini[2] mounted on an HTC Vive. This last setup provides a much more stable head tracking than the Meta 2 (#3) while providing a similar display resolution. The only downside is that the video passthrough does not feel as natural as a true see-through device such as the Meta 2, but we found that #3 would be the most suitable for a systematic user study.

MULTIMODAL INPUT AND DISPLAY SCENARIOS

We can leverage the slider actuation to integrate the Embodied Axes with other input devices to support multi-modal *integrated* and *separated selections* [22]. In fact, some input devices are very efficient for specific tasks. For example, a 2D mouse is very efficient to draw 2D bounding boxes (because it integrates and coordinates the X and Y axis in a single input) or to select a pixel on the screen. Similarly it is very efficient to select an object or point a location in mid-air with an accurate 6DOF tracked device.

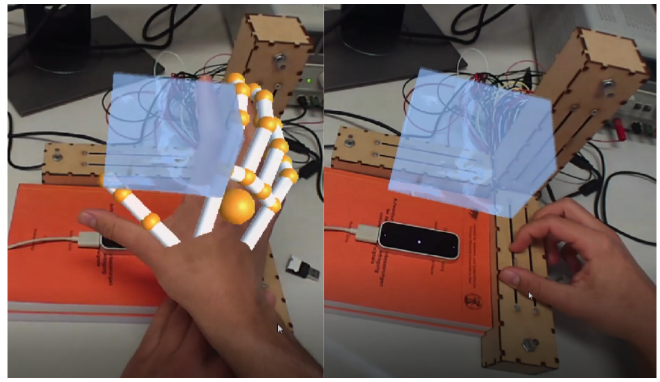

Figure 4: Coordination of mid air selection with actuation of each axis to define a bounding box. This multimodal selections allows a fast 3D selection in mid-air (left) and further refinements with the sliders knobs (right).

Given this, we explored different integrations of the Embodied Axes with easily available input style, such as mid-air hand tracking sensors, and more traditional 2D input devices such as mouse and touch surfaces. Our main focus was to further explore the possibilities of coordinating other types of user input with the actuated sliders for 2D and 3D selections. Since all our prototypes work with Unity, it was convenient to remap the input coordinate values to the actuated range sliders. In the following we present three interaction integrations.

Leap Motion hand-tracking—We placed a Leap Motion controller hand-tracking sensor at the base of the Embodied Axes (Figure 4). We mapped the 3D position of the two index fingers (X,Y,Z position of the left and right hand) to the corners of a 3D box. The minimum and the maximum slider values of each axis followed the dimension of the 3D box defined by the index positions. As a result the sliders move according to the two index positions. This type of interaction allows the user to define a box region *quick and dirty* and then refine the selection with the sliders. Another use of mid-air coordination is the definition of range selection per axis. The distance between two tracked fingers can be used to define a range selection and set the distance between the physical minimum and maximum sliders on the axis. Then by moving the minimum or the maximum tangible slider it is possible to perform a range slide operation (one slider follows the other when it is moved to preserve the range value).

Mouse and touch input—We explored 2D input multimodal integration with the Embodied Axes. We mapped the X,Y mouse coordinates to the horizontal plane spanned by the (X,Z) axes of the Embodied Axes. We prototyped a rubber banding rectangle drawing interaction with mouse drag that actuates the slider knobs to define the rectangle coordinates on the plane. Used in combination with the vertical Y axis of the Embodied Axes we obtain an emergent multimodal selection, that can be used to explore a space-time cube visualisation. For example, the user can first define a selection of a geographical region of

[1] https://www.leapmotion.com
[2] www.stereolabs.com/zed-mini/

interest in 2D with the mouse, then slide the vertical axis to browse through time. This type of multimodal interaction can easily be extend to touch-based or pen-based interactions.

Multiuser integration—Discussions, workshops, and expert enquiries lead us to prototype a collaborative Embodied Axes setup that involved remote collaboration between medical experts, thousands of kilometers apart (See Domain Expert Study). From these discussions, it was recognised that supporting two users to collaborate remotely, each using a physical Embodied Axes, could be beneficial to scenarios such as remote support, particularly for rural communities in our sparsely populated country. To explore this concept, we replicated the Embodied Axes prototype and created a network application in order to connect two users remotely. In this iteration, moving a physical slider on one of the Embodied Axes would replicate that physical action on the remote Embodied Axes. We built and tested this setup between two Australian cities, separated by 1000km. From our informal results, we were able to collaboratively interrogate a 3D medical dataset using the Embodied Axes and video chat software for communication. We observed that the system potentially provided a valuable cue for increasing the sense of presence of the remote collaborator. This observation motivates some of our intended future work (see Limitations and Future Work).

DOMAIN EXPERT STUDY

While we designed the Embodied Axes for multipurpose 3D data visualisation selection, through early experimentation and informal feedback we identified medical imaging as a real-world domain which would potentially benefit from such a system, especially for 3D spatial data such as CT and MRI scans (Figure 1 center, Figure 2 (a)). Those scans provide axis-aligned X-Ray volume data naturally mapping to the Embodied Axes.

Setup

We conducted a study with three experts in medical imaging to obtain feedback about the usability of Embodied Axes and its ability to solve their tasks to analyse gray scale 3D body scans. The experts included a radiologist specialised in pancreas preparation intervention (RAD), a forensic anthropologist (FOR), and a data science engineer (ENG) specialised in 3D medical images reconstruction. We organised a two hours informal interview and mini-workshop at our university. Participants were first asked to introduce themselves to the facilitator and to the others, then answered high level questions on their job and use of medical images. We then asked participants to reflect on current potential issues with their every day setup for visualising and interacting with their data, and enquired about their use of 3D visualisation. We eventually presented the Embodied Axes combined with the Meta 2 headset, showing a volume rendering CT scan of the head of a patient. Experts were given five to ten minutes to interact freely with the device and provide verbal feedback on their general experience. As part of this feedback, they were asked to express what features and possible further usage scenarios they could envision.

Observations

Domain level tasks—RAD uses CT scans of the pancreas to *prepare interventions* that require injections with needles; FOR uses CT images to understand cause of death (e.g. wounds or fractures); and ENG visualises post-processed acquisition of CT data to *assess the quality* of the scanner sensor, looking for artefacts.

Use of 3D stereo images—All experts except RAD use 3D renderings of the CT images, either for a better understanding of a lethal wound (FOR) or to understand the nature of an artifact (e.g., motion blur due to sensor during acquisition of data) in the CT images (ENG). Current 2D and monoscopic 3D images have been reported to suffer from severe occlusion. RAD usually does not use any 3D visualisation of a scan, but rather uses three orthogonal and individual planes. For RAD, the reconstruction of the 3D space serves as a strong mental and cognitive support to build a representation of the organ under observation, to, e.g., plan needle placement (organ depth, needle angle).

Required interactions—All experts reported the requirement to *navigate slices* of a CT scan. FOR and RAD need to *define or select 3D regions* (e.g. bounding boxes) to, for example, select a section of an organ that is to be treated (RAD) or to select a wound on a full body scan (FOR).

Positive feedback—Experts expressed a very positive first impression. They commented on the feeling of precision provided by the tangible sliders as a pleasant, impressive experience and reported they could see a lot of potential applications for the control device.

Possible Improvements—A major issue was head rotation; all experts tried to get on the sides and/or behind the 3D visualisation to change their point of view on the CT scan. They suggested solutions such as mounting Embodied Axes on a rotatable base, making axes remappable, e.g., by using the knobs attached to each axis. They further mentioned that the rotatory knob could control general visualisation parameters such as intensity and contrast. RAD envisioned using the sliders to measure distance between two regions of a CT scan, or define a region of interest; it would also be useful if there was a possibility to track a needle in the 3D volume and to define the injection regions as well as to also draw 2D and 3D contours around soft tissues.

Possible usage scenarios—Embodied Axes could be used as a complementary device to desktop (screen, mouse, keyboard) setup (ENG, FOR); the desktop setup, because of large display size and high resolution, allows very good visual exploration of data artifacts in the CT image visualisation; Embodied Axes would sit next to the screen for interaction if required. Embodied Axes could also help during court cases as a presentation tool for lawyers, e.g. next to a body during an autopsy (FOR), or to prepare complex operations by tracking a needle inside the volume to define injection areas for pancreas lesions (RAD). Eventually, all experts mentioned the need for collaboration, citing the need for their city-based institutions to support remote and rural regions for both medical diagnoses (RAD, ENG) and criminal investigation (FOR). Such collaboration could be supported either through synchronised mixed reality displays, or through an additional monitor.

This study was formative in the sense that it informed the tasks evaluated in our controlled study and ensured their ecological validity. That is, in our controlled study (next Section) we test two visual tasks that correspond to the low level tasks reported by the medical professionals (RAD, ENG): slice selection (*Slice Finding task*) and definition of a 3D region of interest (*Bounding Box task*). Our study also provides directions for future work (Section *Findings And Discussion*).

CONTROLLED USER STUDY

Informed by the domain expert feedback, we set out to compare the constrained tangibility afforded by the sliders of the Embodied Axes with mid-air interaction to perform low-level selection and visualisation tasks. Our initial intention was to use finger tracking with the Leap Motion controller for the mid-air condition, as per Figure 4. However, through pilot testing we found the Leap Motion controller unable to accurately track fingers in all hand poses resulting in selection significantly less precise and robust than what is achievable with the Vive controllers. Kinect[3] and the built-in hand tracking of the Meta 2 had similar issues. Hence, we compare Embodied Axes to the Vive's Tracked Controllers as a substitute for mid-air interactions as it is the most reliable default input device provided with common VR and AR devices. The Vive controllers are tracked at a 0.5mm accuracy when stationary and allow to perform precise and small VR interactions. We may revisit this investigation as new technology becomes available (e.g. the forthcoming Microsoft HoloLens 2 release with improved finger tracking).

We set the focus on three main tasks: 1) setting a value on an axis, 2) selecting a slice in a 3D volume, and 3) perform a bounding box selection task in a 3D visualisation. Those tasks investigate 1D, 2D and 3D selection respectively.

The visualisation and interaction space we study is within a volume of $100 \times 100 \times 100mm$. This volume, while relatively small, corresponds to a size that makes sense for scale for medical practitioners. It also corresponds to a desktop-size display of a 3D visualisation that could be used in combination to the 2D screen and, due to its size, may be less prone to "gorilla arms" effect [4, 20].

Tasks and stimuli

Target task—In this task, a participant saw a value on one of the axes and had to (1) move a virtual pointer (in the virtual condition) or their hands (with Embodied Axes) towards the slider knob, (2) acquire the slider knob, (3) slide the knob to the target value and (4) release the knob. The value represented by the slider was visually attached to the slider and was updated when the participant moved the slider. Values from the potentiometers were used, rounded to the nearest 10 in the range 0 to 1020 based on experimentation; this corresponds to 1mm precision as a conservative limit of the slider potentiometers. Between each task the slider cursor was reset to the center value. *Participants were instructed be as precise as possible.* This task aims to directly compare 6DOF and controller-based interaction to tangible sliders. Thus, we replicated slider and slider interaction in in the virtual condition, rather than directly pointing to the target value in the virtual environment which is not possible with tangible sliders.

[3]https://www.microsoft.com/en-us/p/azure-kinect-dk

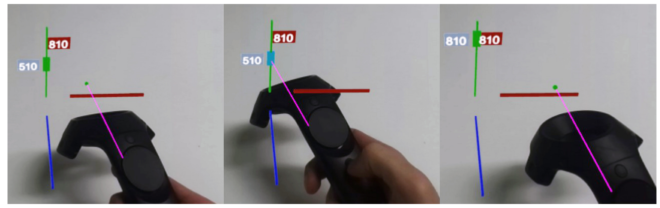

Figure 5: Target task in the Tracked Controllers condition.

Slice Finding task— In this task participants viewed a volume visualisation rendered with a 3D cube matrix. We placed 3 to 5 spheres (4 stimuli with 3 spheres, 4 stimuli with 4 spheres and 4 stimuli with 5 spheres) with different diameters inside the volume. The diameter of the biggest sphere was controlled to be at least 10% bigger than the next big sphere to ensure that the task could be achieved. The task consisted of slicing the volume in depth by moving one slider with the aim of finding the slice that corresponds to the center of the largest sphere. Participants had to slice the whole volume to find all spheres in order to select the correct slice. *Participants were instructed be as precise and as fast as they were able.*

Bounding Box task— In this task the participants viewed a 3D scatterplot composed of blue and red dots. The red dots belonged to a dense cluster placed in 3D among the blue dots. Participants had to draw the smallest 3D bounding box capturing all red dots. The dots that were not in the bounding box selection were highlighted semi-transparent, while the selected ones were fully opaque. This indicated the current selection to the participant. *Participants were instructed to be as precise and as fast as they could*

Interaction Techniques

Participants were asked to perform the above tasks with the Embodied Axes and with the Tracked Controllers technique.

Tracked Controllers Technique— In the Tracked Controllers technique we used the HTC Vive 6DOF handheld tracked controllers. We positioned a 5cm long ray pointing out of the controller. A small 3D sphere cursor (0.5cm diameter) was placed at the end of the ray to enable interaction. To interact with the components we used a common VR pointing and intersect interaction [28]. This interaction consisted of colliding the 3D cursor with a target object; pull the trigger of the VR controller to drag the object; and release the trigger to position the object.

In the Target task participants had to collide the 3D cursor with the virtual knob of the slider (which was then highlighted, Figure 5 (center)), pull the trigger to move along the axis (the slider knob was constrained to move along the X, Y or Z axis) and release the trigger to set the value (Figure 5 (right)).

In the Slice Finding task for Tracked Controllers (Figure 6), participants had to place the controller inside the volume visu-

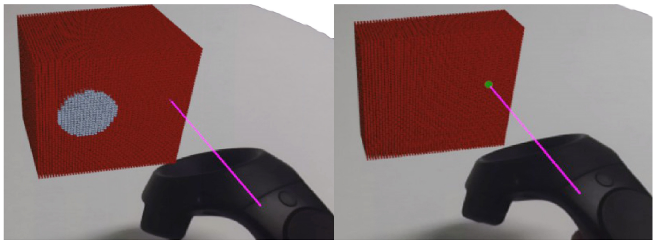

Figure 6: Slice Finding task with Tracked Controllers.

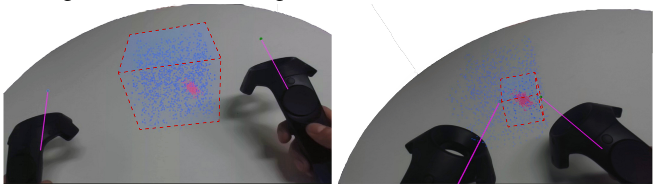

Figure 7: Bounding Box task in the Tracked Controllers condition (red dashed outline around the 3D box added for illustration purpose.)

alisation, pull the trigger on the controller and move it back and forth along the depth axis to slice the volume. When the participant released the trigger the volume remained sliced at the last cursor position.

The Bounding Box task in the Tracked Controllers condition (Figure 7) consisted of a rubber banding 3D cube drawing controlled with bi-manual interaction to *draw the bounding box*. The cube was defined by two control points: a top left front point controlled by the left controller cursor, and a bottom right back point controlled by the right controller cursor. Participants had to pull the two triggers on the each controllers to start drawing the bounding box. The bounding box was set when both triggers were released.

Embodied Axes Technique — In the Target task for the Embodied Axes condition, participants had to slide the physical knob on the slider to the target value (Figure 8 (left)). For the Slice Finding task, participants moved one slider (an overlay indicated the slider to move) along the Z axis of the Embodied Axes to browse the 3D volume (Figure 8 (center)). The parameters of the 3D box for the Bounding Box task were defined by the minimum and the maximum sliders positions on each axes of the Embodied Axes (Figure 8 (right)). Hence participants had to control 6 values to define the bounding box. For comprehension during the experiment we added overlays over each slider knob.

Hypotheses

In this study, we test Null-hypotheses for task-completion time and error-rate (i.e., no differences) since we compared Embodied Axes to the baseline technique Tracked Controllers for the Target Task (H1), Slice Finding Task (H2) and for the Bounding Box Task (H3).

Participants

We recruited 12 participants (mean age = 29, $SD = 6.8$) from our lab, all participating voluntarily. They were postgraduate students, PhD students and faculty members, and were all right-handed. Participants were asked to report their previous

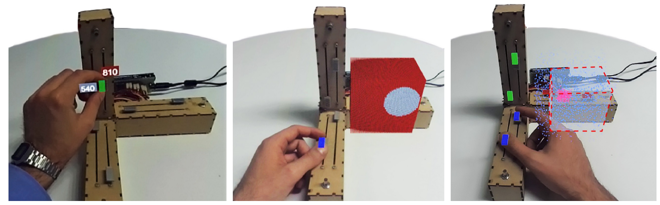

Figure 8: Target task (left), Slice Finding task (center) and Bounding Box task (right) in the Embodied Axes condition. The red dashed outline around the bounding box was added for illustration purpose.

experience with AR/VR, visualisation and mid-air interaction on a five points Likert Scale (ranging from 1, not familiar, to 5, very familiar). They reported being rather familiar with VR/AR ($M = 4.2, SD = 0.94$), also rather familiar with data visualisation ($M = 4.2, SD = 0.85$), and quite familiar with mid-air interaction ($M = 3, SD = 1.4$).

Experimental setup

We used the HTC Vive headset and controllers with a ZedMini stereo pass-through camera. The resolution of the video pass-through feed was 720p with a refresh rate of 60hz, which made it suitable for an hour long use. To ensure a high framerate for optimal usability in the study, we used a desktop PC computer with an Intel i9 2.8GHZ, 64GB of RAM and a Nvidia GeForce RTX 2080Ti graphics card. We used the Immersive Analytics Toolkit (IATK) [9] to implement efficient interactive immersive visualisations in the study.

During the study participants were sitting at a round table, and interacted over the tabletop for both Tracked Controllers and Embodied Axes Techniques. For both techniques we asked participants to reset their hand positions between each trial:

- with the Tracked Controllers technique participants were instructed to put their hand holding the Vive controller back on a red sheet on the table between each trials;
- with the Embodied Axes condition participants were instructed to put their hand back next to a token.

Experimental design

We used a 2 × 2 Latin Square to counter balance the Technique (Tracked Controllers, Embodied Axes), and a within participant design. Six participants started with the Embodied Axes Technique and six participants started with Tracked ControllersTechnique. Since we were not testing for performance between tasks, the tasks appeared in the same order (first Target, then Slice, then Bounding Box). However the trials within each tasks were randomised. We collected a total of 2 (Techniques) × 12 (Participants) × (24 *Targets* + 12 *slices* + 12 *Bounding Boxes*) = 1,152 trials.

Measures

For all tasks we measured completion time (in seconds) and error. For the Target task, error was the maximum overshoot (or undershoot) over or below the target value. For the Slice Finding task, error was the distance to the slice (in number

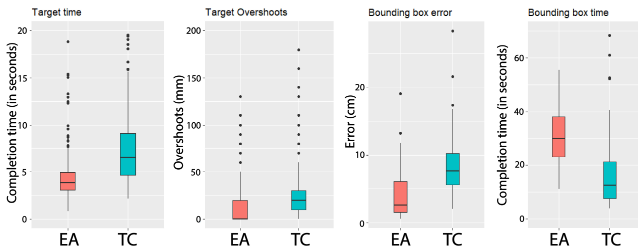

Figure 9: Error and completion time for Target and Bounding Box tasks for the Embodied Axes (EA, red) and Tracked Controllers (TC, green).

of slices) at the center of the largest sphere. For the bounding box task, we summed the distances between each of the eight corners of the computed optimal bounding box to the corresponding one defined by the participant. In a post-study survey, we measured overall perceived physical fatigue for each Technique on a five-point Likert scale. We also captured overall Technique preference.

Procedure

Participants were welcomed in a faculty room and were first asked to answer a short demographics survey (age, background, previous experience with VR/AR and mid-air interaction). They were then explained the aims of the research and the experiment. Participants then proceeded to perform the three tasks starting with either the Tracked Controllers or the Embodied Axes Technique. Between each tasks, participants took a break and were instructed with the next task. At the end of the experiment participants were asked to fill a post-study survey. The whole study took on average an hour to complete.

RESULTS

For all tasks, time and errors were not normally distributed. Since our experimental design was within participants, we used the Wilcoxon test to measure the statistical difference between Techniques. As the data was not normally distributed, we report median values for the results.

Time and errors

Target Task Results—Embodied Axes ($Mdn = 3.8s$) was significantly faster than Tracked Controllers ($Mdn = 6.7s$) for the Target task ($W = 27783, p < 0.05$) and had significantly less error ($Mdn = 0$) than the Tracked Controllers ($Mdn = 20$) ($W = 40984, p < 0.05$). H1 can be rejected as we found differences between the two techniques.

Slice Finding Task Results—No significant difference in time was found between Embodied Axes ($Mdn = 5.5s$) and Tracked Controllers ($Mdn = 5.9s$) for slice finding. No significant difference in Slice Finding error was found between the two conditions (1 slice error). H2 cannot be rejected as we did not find a significant difference between the two techniques.

Bounding Box Task Results—For completion time, the Embodied Axes ($Mdn = 29.9s$) was significantly slower than the Tracked Controllers ($Mdn = 12.5s$) technique ($W = 17551, p < 0.05$). Embodied Axes ($Mdn = 0.25m$) was found to have significantly less Bound Box error than the Tracked Controllers ($Mdn = 0.76m$) technique ($W = 3345, p < 0.05$). Hence H3 can be fully rejected as we found a difference between the two techniques.

Post-study survey

All participants indicated that they felt that Embodied Axes allowed them to perform more precise selections. Additionally, 9 out of 11 participants indicated a preference for the Embodied Axes to perform selection tasks in the future. On a five point Likert scale (1 not fatiguing to 5 very fatiguing), Tracked Controllers was found to be significantly more fatiguing ($M = 1.7, SD = 0.5$) than the Embodied Axes technique ($M = 3.6, SD = 1$).

FINDINGS AND DISCUSSION

Our results show that Embodied Axes is a usable and efficient design for selection in 3D visualisations and confirms hypotheses described in [8] about the concept of spatio-data coordination. Our work contributes to the wider discussion around design choices for building such devices, including for immersive tangible AR in general. In particular, we conclude with the following findings.

Precise value selection on axes—The results of the first task found that participants were on average 56% faster and made less overshoot with the Embodied Axes than with the Tracked Controllers (C1). The difference in speed and accuracy is substantial and support our design choice for value selections. Our results confirmed previous findings [24] about using sliders for remote control on Wall Size Displays. Our results extend this knowledge and validate their use for 3D immersive AR visualisation. While we have not tested range sliding interaction (which requires to set two values per axes and move the range along the axes), we can predict that Embodied Axes will be at least twice as fast than Tracked Controllers. In general, participants reported that the Targets task was particularly difficult to achieve with the Tracked Controllers Technique. We observed that three participants had to hold their primary pointing hand with their other hand for support in order to achieve precision. We also observed a lot of jitter due to hand shaking. All participants reported that they felt more precise with the Embodied Axes and results show that they were significantly faster and had less overshoot. This provides evidence to support the benefit of the tangible controller for value selection on a visualisation axis or frame of reference. We presume that Embodied Axes prevented the Heisenberg effect [5], which is a common issue with mid-air and controller-based interaction for precise selection in space.

3D Volume browsing well supported—Time and accuracy for the Slice Finding task were similar with the two techniques. Our result seem to indicate that volume browsing is as suited for the Embodied Axes as for the Tracked Controllers. However we believe, based on our post-study survey, that the Embodied Axes could be a better choice in cases where a great deal of repeated volume browsing interactions are needed, as it would reduce fatigue. Additionally our slice selection task was rather coarse (the volume was only $50 \times 50 \times 50$ voxels),

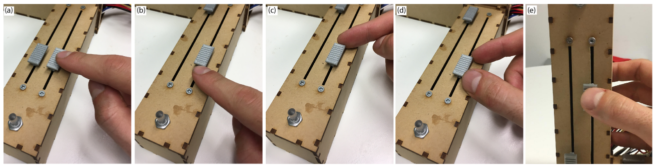

Figure 10: Observed different finger poses on the sliders.

but real applications e.g. medical imaging visualisation would require users to select and browse much larger volumes.

Bounding box selection more precise—Participants were on average three times more precise with the Embodied Axes than with the Tracked Controllers to make the bounding box selection. This can be explained by the fact that with the Embodied Axes, once a value is set on an axis (e.g. the maximum x value to define the horizontal dimension of the 3D box), the value persists until changed, as the physical slider does not move. This allows for iterative refinement of the bounding box resulting in greater precision, whereas the Tracked Controllers rubberband interaction techniques does not support this iterative refinement. However, iterative refinement of the Embodied Axes interaction has a time cost which was reflected in our result (the Tracked Controllers technique was on average 2.5 times times faster than the Embodied Axes).

Tangibility appreciation and usage strategies—Open feedback from participants indicated that they liked the Embodied Axes because of its tangibility. To our surprise, we observed participants manipulating the slider knobs using multiple strategies. The perceived affordance of the physical knob would suggest placing the fore-finger on the knob's depression and moving the hand (Figure 10a), however we observed participants nudging the front or back of the knob (Figure 10b–c) with their finger, or holding the knob between their fore-finger and thumb (Figure 10d). Another common manipulation strategy we observed specific to the vertical axis involved the participant supporting their hand behind the axis with their fingers and manipulating the slider with their thumb (Figure 10e). We also observed participants leaning around the 3D visualisation, presumably to leverage kinetic motion to perceive the 3D structure properly.

Towards an integration of mid-air and tangible sliders—The physical sliders allow for more precise 3D selection and our study results show that colocation of interaction and visualisation is important, confirming results from previous studies on interaction with immersive visualizations [3]. However, it is slow in comparison to what can be achieved with mid-air interaction. Some participants mentioned that the bounding box task felt frustrating to achieve with the Embodied Axes even though they were significantly more accurate. Two participants also reported that drawing the 3D bounding box with the mid-air interaction, while intuitive, required relatively high mental effort and coordination.

The results of our study and our observations lead us to believe that a suitable interaction for accurate and fast selection require both mid-air for quick selection and tangible sliders for adjustments. Ideally, the mid-air control would be with precise finger tracking rather than tracked controllers – which would need to be picked up and put down to switch modality. We demonstrate a prototype of multimodal interaction using the Leap Motion finger tracking device in the video which accompanies this paper. The demonstrated multimodal interaction is comparable to the multiple ways of interacting with standard 2D box selection UI. That is, the slider knobs act as "thumbs" that follow the rubber banding 3D mid-air selection interaction, and the sliders are then ready in position for precise manipulation once a rough selection is made. However, as mentioned earlier, the current generation of mid-air finger tracking technology is not yet sufficiently accurate for fine interactions and so we have not yet conducted a user study that examines such interaction.

LIMITATIONS AND FUTURE WORK

The dimensions of the device are largely dictated by the actuated linear potentiometer devices we used, which are produced in high-volume for use as fader controls in AV devices. Reliance on such commodity devices means the fabrication cost of the physical device is under US$100 and potentially allows for cost-effective mass production. In the future, we will explore the use of more specialised linear potentiometer devices to allow for a larger interaction volume.

Our controlled user study is limited to the choice of tasks we evaluated and by the input modality (tracked controllers) used to compare with the Embodied Axes. In the future, we would like to investigate comparison with fine mid-air interactions that can be achieved through forthcoming tracking technology, such as is touted for Microsoft Hololens 2. Further, we would like to explore applications of the device beyond medical data visualisation, for example to engineering applications and more general scientific and information visualisation.

In our study only right-handed participants were involved. This was due to our current Embodied Axes design which is designed for right-handed users (the X axis of the Embodied Axes is placed on the right side of the controller). In future work, minor modifications would be required to enable use with either hand and obtain feedback from left-handed users.

Finally, while we intended to explore collaborative use cases with the experts involved in our formative study, due to the novelty of the device, the participants focused on the usability and the potential of application for their work. However, collaboration (both local and remote) with the Embodied Axes will be examined in a future study.

CONCLUSION

In this paper we presented the design and the evaluation of Embodied Axes, a low-cost, precise selection device. Our main findings regarding data selection for 3D immersive visualisation are that 1) constrained tangible control offers more precise selection with no reported fatigue, and 2) tasks that require more integrated control, such as defining a 3D bounding box, are more precise with the Embodied Axes but were perceived to be difficult, and are faster with mid-air interaction but less precise. Our initial expert enquiries identified the relevance of use of such device in the medical imaging domain and are motivating our future research.

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