The MADE-Axis: A Modular Actuated Device to Embody the Axis of a Data Dimension

JIM SMILEY, BENJAMIN LEE, SIDDHANT TANDON, MAXIME CORDEIL, and LONNI BESANÇON, Monash University, Australia
JARROD KNIBBE, University of Melbourne, Australia
BERNHARD JENNY and TIM DWYER, Monash University, Australia

Tangible controls—especially sliders and rotary knobs—have been explored in a wide range of interactive applications for desktop and immersive environments. Studies have shown that they support greater precision and provide proprioceptive benefits, such as support for eyes-free interaction. However, such controls tend to be expressly designed for specific applications. We draw inspiration from a bespoke controller for immersive data visualisation, but decompose this design into a simple, wireless, composable unit featuring two actuated sliders and a rotary encoder. Through these controller units, we explore the interaction opportunities around actuated sliders; supporting precise selection, infinite scrolling, adaptive data representations, and rich haptic feedback; all within a mode-less interaction space. We demonstrate the controllers' use for simple, ad hoc desktop interaction, before moving on to more complex, multi-dimensional interactions in VR and AR. We show that the flexibility and composability of these actuated controllers provides an emergent design space which covers the range of interactive dynamics for visual analysis. In a user study involving pairs performing collaborative visual analysis tasks in mixed-reality, our participants were able to easily compose rich visualisations, make insights and discuss their findings.

CCS Concepts: • **Human-centered computing → Haptic devices**; **Visualization systems and tools**; • **Computing methodologies → Mixed / augmented reality**.

Additional Key Words and Phrases: data visualisation, embodied interfaces

ACM Reference Format:
Jim Smiley, Benjamin Lee, Siddhant Tandon, Maxime Cordeil,, Lonni Besançon, Jarrod Knibbe, Bernhard Jenny, and Tim Dwyer. 2021. The MADE-Axis: A Modular Actuated Device to Embody the Axis of a Data Dimension. *Proc. ACM Hum.-Comput. Interact.* 5, ISS, Article 501 (November 2021), 23 pages. https://doi.org/10.1145/3488546

501

1 INTRODUCTION

The rapid advance of computers has seen more and more data manipulation disappear into circuits and software. Traditional data visualisation has, at best, given us a window into this electronic realm. Immersive display technologies, such as augmented and virtual reality, offer to bring images of data back out of the computer and "into the world around us". Making it possible to touch and feel these representations of data is a difficult design challenge, yet it is important to address if we are to properly use our full human sensory abilities to explore data.

Authors' addresses: Jim Smiley, jim.smiley@monash.edu; Benjamin Lee, Benjamin.Lee1@monash.edu; Siddhant Tandon, siddhant.tandon@hotmail.com; Maxime Cordeil, maxime.cordeil@gmail.com;
Lonni Besançon, lonni.besancon@monash.edu, Monash University, Australia; Jarrod Knibbe, jarrod.knibbe@unimelb.edu.au, University of Melbourne, Australia; Bernhard Jenny, Bernie.Jenny@monash.edu; Tim Dwyer, tim.dwyer@monash.edu, Monash University, Australia.

2573-0142/2021/11-ART501 $15.00
https://doi.org/10.1145/3488546

Quantitative data visualisation revolves around the concept of mapping quantitative data dimensions to a spatial axis. In this paper we introduce the *MADE-Axis*, a Modular Actuated Device to Embody an Axis. The lightweight, hand-sized, cordless device features actuated sliders, a rotary encoder and button for spatio-data coordinated interaction [12]. Past research has demonstrated benefits of tangible, mixed-reality systems to enable new pathways in our understanding of complex data. As sophisticated as some of these past systems have been they are yet to find widespread application outside of research labs and challenges remain to create devices for data manipulation that are practical.

Compared to past devices for interacting with data visualisations (Sec. 2), we contribute a novel device with a set of interaction affordances that are particularly supportive of the practical interactive dynamics of visual analysis (Sec. 4). In particular, the MADE-Axes are: (1) easy and affordable enough to build that many units may be constructed and used in powerful combination (Sec. 3); (2) flexible enough to support a variety of use cases (Sec. 5); and (3) robust, small and light enough to support hand-held use in mixed-reality scenarios, where (4) it has a particular strength as an embodied affordance for visualisation control, which can be physically shared in collaborative scenarios, as demonstrated in a qualitative user study (Sec. 6).

2 RELATED WORK

Our work is directly related to immersive analytics research [51]. We build on multidimensional data visualisation authoring and exploration by leveraging tangible interaction, actuation and composability.

2.1 Tangible interaction in visualisation

Tangible interaction aims at leveraging and mimicking natural human manipulation of objects in their 3D environment [20, 33]. Past research demonstrates that tangible interaction is useful to provide fast and precise 3D manipulations [3], to foster collaboration [52, 53], and to provide engaging immersive experiences [3, 70]. Such results make tangibility an interesting candidate for visualisation research projects and tangible interfaces have been one of the most studied interaction paradigms for interaction with 3D spatial data in visualisation [5].

A pioneering example by Hinckley *et al.* [28] used tracked props for neurosurgeons to explore the internal structure of their dataset by manipulating cutting planes. Following this example, many research projects have created tangible props for a specific purpose. For example, Schkolne et al. [57] used custom tangible devices, such as a gun, to explore and manipulate DNA datasets in VR. Jackson *et al.* [35] used a paper roll to create a tangible prop to select thin fiber structures. Gomez *et al.* [24] combined two tracked devices: a pen-like probe to brush in a 3D volume and a cube to manipulate the data, while De Haan *et al.* [16] combined a pen-probe and a transparent acrylic plane to help select regions of interest in 3D data. Issartel *et al.* [34] created a 'cuboctahedron' to manipulate fluid dynamics data with 6DoF in handheld AR, providing additional props (e.g., a stylus) to manipulate a cutting plane or place seed points in 3D.

Other researchers have tried to use pre-existing devices (some with built-in tracking solutions) to increase their versatility. Cassinelly and Matasoshi [8] used a tracked screen to facilitate exploration and annotation of medical data. Song *et al.* [60] and Lopez *et al.* [48] used a similar approach, combining a smartphone/tablet with a large vertical display. Besançon *et al.* leveraged the built-in tracking of the Google Tango tablet combined with its tactile screen to propose data and cutting plane manipulation or seeding point placement [2] as well as 3D extrusions of 2D lasso shapes for 3D selection of spatial data [4]. Spindler *et al.* [61, 62] made use of tracked props to support a variety of visualisation tasks ranging from augmenting an existing visual representation with colours to providing different levels of abstraction.

On the spectrum between specialised and generic devices, the work of Cordeil *et al.* [11] stands out. Their work highlighted a novel approach to controller design with the concept of *spatio-data coordination*[13]. Where most specialised controllers use novel mechanisms to achieve a specific goal (i.e., simulating weight or momentum), their *Embodied Axes* explored the application of a standard, common component – the actuated slider. Paired sliders were mounted on three orthogonal axes, to create a volumetric range selector. In this paper we generalise the *Embodied Axes* concept from a specialised 3D interaction device, to universal controllers – not only for spatial data with three orthogonal dimensions, but to any number and spatial or non-spatial configuration of quantitative and categorical data dimensions. While Cordeil's Embodied Axes system had three table-mounted axes fixed orthogonally to provide a 3D interaction space, we explore the value of decoupled (wireless and modular) axes controls that can be handheld or placed in various combined configurations to cater to a variety of applications.

2.2 Actuated visualisations and devices

Haptic feedback has been explored in visualisation using specific commercial devices (e.g., PHANToM [49, 50, 66, 67]) or lab prototypes (e.g., [47]). While most physical visualisations are inert, actuation can make them dynamic and interactive (see e.g., [36]). Actuated systems can represent physical "pixels" representing binary values or a range of different values. Many of these systems rely on arrays of motorised bars [22, 45, 54, 64], while some provide a more continuous control of the final shape [21, 55]. The physical pixels of these systems can be mapped to data values in order to allow physical visualisation to represent non static data [22, 44, 64]. The primary focus of these systems is to provide some control over a specific topology or geometry. Yet, only a handful of these systems facilitate interaction (see e.g., [64]). It must be said that these systems are also typically expensive to manufacture, large and unwieldy.

To provide a more versatile control of geometry and interaction techniques, Le Goc *et al.* [40, 41] introduced Zooids: small robots that can rearrange themselves on a table in order to provide several visual representations and adapt to the data. In addition to the versatile output they produce, they can also be used as flexible controllers to interact with the data with filtering, picking, and dimension selections. Our work directly takes inspiration from these, but rather than aiming to provide actuation per data point, we target an axis as an embodiment of an entire data dimension and as the primary affordance for interaction (inspired by the work by Lischke *et al.* [47] and Cordeil *et al.* [14]).

2.3 Composability in visualisation

The concept of interactive composition of visualisation elements to allow users to create rich displays has become fairly standard for data visualisation software [37]. Classen and Van Wijk [10] demonstrated the use of *axes* (linear representations of data dimensions) as the elements of composition. Several systems have drawn inspiration from this work since then [25, 68] and have all been designed for 2D, desktop-style non immersive and non embodied setups.

In contrast, our work focuses on data visualisation composability with embodied interaction in mind [17] – the MADE-Axes are designed to embody a data dimension with a device that can be manipulated and positioned in the user's space to compose visualisations. Previous work has investigated how embodied interaction helps users organise and compose their workspace with tangible representations of data (e.g., air traffic controllers compose paper strips [46, 56] representing flight data). Huron *et al.* [30, 31] explored the use of simple building blocks to build data physicalisations.

We also see MADE-Axes as composable building blocks for interacting with data. One inspiration for this work is *parameter bars* by Ullmer *et al.* [65]. They combined sliders and a display into a device that could filter attributes along a data dimension. *Parameter bars* were combined to interact with multiple dimensions: when the bars are adjacent a Boolean "AND" operation is applied, and when they are spatially separated a Boolean "OR" operation is applied. However, the combination of these devices was through attaching them to a slotted rail rather than free-form position (as we explore in this work). Further, they did not explore the possibilities of actuation of the sliders. With *ImAxes*, Cordeil *et al.* [14] explored the construction of multivariate visualisations with data axes as building blocks in virtual reality, but using standard VR controllers. Batch et al. [1] further studied how data scientists leverage the 3D space to compose, organise and explore their visualisations with *ImAxes*. Strongly related to these approaches, Khadka *et al.* [38] proposed the use of discs to represent slices of a dataset that can be spatially rearranged and even worn by users.

MADE-Axes physicalises the virtual axes composition explored in *ImAxes* [14]. and the composable tokens explored by *parameter bars* [65], but with greater possibility for tracked control, actuated haptics, and application to a greater variety of visualisation types and Use Cases including mixed-reality (Sec. 5).

2.4 Immersive Analytics

Immersive Analytics aims at combining several research fields to better support data analysis with immersive technologies [19, 51]. As an emerging field, it currently faces a number of key research challenges [19]. We focus here on two of these key challenges. The first, "Supporting transitions around immersive environments" [19], pertains to the inherent need of analysts to combine several working environments, such as a desktop station (for its powerful computing power and variety of software tools) and an immersive context (for its ease of use). To address this challenge, past research has looked into using classical desktop input devices (mouse and keyboard) or touch devices in immersive settings [6, 23, 26, 69]. In contrast, with MADE-Axes we create a device for immersive setting that also present some affordances for classical desktop workstations with its two sliders.

The second challenge pertains to "supporting behaviour with collaborators in immersive settings" [19]. Collaboration scenarii are rarely explored in augmented reality [59]. In most cases, they involve a singular shared visualization between all users [43], while some approaches relied on mobile devices with touch screens in immersive context to allow for collaborative analysis [7, 9, 29]. In our work, however, we propose to use multiple MADE-Axes devices: they can be used by several users independently, combined and collectively manipulated, and their inherent tangible properties afford for more natural collaboration patterns [52, 53] between users.

3 THE MADE-AXIS

Our initial motivation was to deconstruct our Embodied Axes [11] device in order to make it **modular**, **wireless**, and **re-configurable** for different data visualisation scenarios. To reach this goal we designed and built individual axes controllers that could then be arranged in different layouts, or used as controllers for visualisation applications. This form factor suits visualisation applications particularly well since most visual representations rely on a Cartesian coordinate system.

The MADE-Axis is designed to offer six key affordances for data interaction in terms of *input*, *output*, and *composability*, as follows:

Input:

Pose position and orientation for spatio-data coordination.

Data-type appropriate physical controls (linear and rotational) as well as a button for selection or mode switching.

Output:

Synchronised visuals via coordinated screen display or in-situ to the device through augmented or virtual reality.

Actuated sliders for automated movement of the controls to data-determined positions or data haptics.

Composability:

Multiple MADE-Axes to embody a multidimensional data space.

With other devices such as screens, headsets, motion tracking, etc.

To achieve these capabilities the controllers must be lightweight and handheld. Further, to support reconfigurability, the devices should be easy to place laying down or standing on a range of surfaces.

3.1 Hardware Design Details

We fabricated an aluminium case to host two sliders, push button and push rotary knob. The push button was an addition to the previous *Embodied Axes* design [11], to better support switching between interaction modes. Additionally, we moved the rotary knob to the the front face of the controller, to axis-align its input - for example, allowing the knob rotation to be congruent with rotation of 3D volumes around the axis.

Each device consists of two 100mm actuated slide potentiometers (Bourns PSM series), a rotary encoder with push switch (Alps EC11E series), a momentary push button with integrated LED, and an ESP32 based micro controller development board with onboard Bluetooth. Each device also houses a 1200mAh Li-ion battery and four custom printed circuit boards - a slider board (one per slider), a distribution board, and an encoder mounting/filter board. Current draw is around 160mA at 3.7v during bluetooth transmission.

Each slider motor is controlled via pulse width modulation, with a frequency of 25kHz in order to prevent the motors becoming audible. The motors can be controlled to provide haptic feedback. This is achieved by activating the motor in both directions sequentially for a time period of 2ms in each direction, with the force controlled by pulse width.

The MADE-Axis is also designed to support a spatio-data coordinated input space. To this end, we track the spatial orientation of the device in 3D space. This allows the devices' orientation to be used to infer relationships to both axes and data points. To achieve 3D tracking of the controller, we attach a unique pattern of 3-5 passive IR markers onto the ends of the device and track it using an 8-camera Vicon motion capture rig. This enables sub-millimeter-level tracking precision. Each MADE-Axis is connected via a standard bluetooth serial COM port.

We reused the same minimal API that we developed for the Embodied Axes [11] to create high-level applications. The Windows MADE-Axis driver allows the programmer to: **Drive** each slider knob along their axis to match a given position; **Pulse** each slider knob for haptic feedback; **Read** the current slider knob position; **Read** the state of the push button; **Read** the rotation steps and the push state of the rotary button; and **Set** the brightness of the LED via pwm. This minimal set of low level commands was used to build all the higher level applications presented later in this paper.

We provide all design files, component information, and driver code at github (anonymised - see appendix for submission).

3.2 Interacting with MADE-Axes: Basic Behaviours

In this section we briefly describe how the MADE-Axis hardware design supports a variety of modes of interaction with data visualisations, with forward references to the use-cases (Section 5) that illustrate their use in greater detail. The mappings of MADE-Axis interaction affordances to

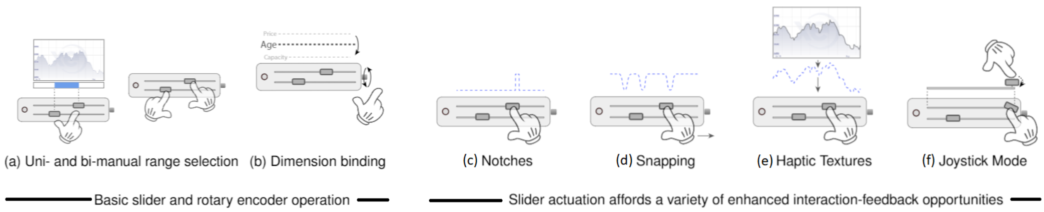


Fig. 1. Basic operations (left) and slider actuation (right).

visualisation operations listed here is intended to be illustrative, not complete. In Section 4 we more thoroughly explore the possibilities of MADE-Axes to support the full range of data visualisation interactions.

Each MADE-Axis affords 11 degrees of freedom (DoF) of *Input*: Sliders (2 DoF), Push Button (1 DoF), rotary click button (2 DoF), and (optionally) their spatial orientation (6 DoF).

Without spatial tracking the controllers can be manually placed to align with the corresponding visualisation dimensions. With spatial tracking their data binding can be inferred from position, making it ideal as a hand-held controller in immersive (VR or AR) data visualisation (Use Case 5.2.1) or as a direct physical embodiment of an axis in mixed-reality scenarios (Use Case 5.2.2). Actuation of the sliders also gives them an *Output* affordance, providing a myriad of data-informed interaction possibilities.

Finally, when multiple MADE-Axes are combined, or individual MADE-Axis are combined with an additional display, further interaction opportunities emerge, see *Composability* 3.2.1.

Basic operation – The sliders form the core of data interaction with the MADE-Axis, affording direct manipulation of the slider knobs to select a range of values along a dimension, see Fig. 1a. In typical use, the left slider selects the minimum value of the range and the right slider selects the maximum. The controller is small to allow range selections to be performed with a single hand (unimanually). This allows the controller to be held in one hand while the other performs the range selection. Alternately, the controller may be placed on a surface (table or horizontal screen) and range selection performed bimanually. The rotary encoder is used to scroll through the dimension being visualised, see Fig. 1b. The push button switches modes to enable haptics and automation behaviours.

Actuation – The sliders' actuation affords a variety of enhanced interaction-feedback opportunities and we designed a series of associated behaviours, across both *haptics* (tactile force-feedback) and *automation* (automatic movement of the sliders to specific positions). These depart from those presented in Embodied Axes [11] (which included *coordination* and *follow mode*). For completeness, we present the full range of behaviours, including those previously discussed in Embodied Axes.

First, the actuation can create the sensation of *notches* along the sliders' travel, see Fig. 1c. These notches can be used to convey data features, navigate discrete data step by step (e.g. dates) or present previously highlighted points to the user.

Second, the actuation supports creation of resistance (the slider knob resists push) and pulling (the slider knob is attracted to a specific point on the slider), see Fig. 1d effects. Combining resistance and pulling allows to create *snapping* behaviours, effectively changing the linear slider between continuous and categorical input. This is achieved by varying the resistance of the sliders' travel, giving the sensation of being pulled toward a hard point.

Third, the resistance along the slider can be mapped to the data itself, creating data *textures* that the user can feel as they move along the slider (inspired by Strohmeier et al. [63] and Lischke et

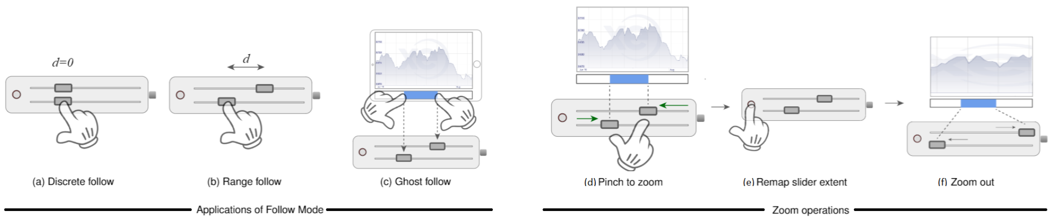


Fig. 2. Filter and zoom using follow mode to pan and joystick mode to expand zoom extent

al. [47]), see Fig. 1c. Moving the slider knob along the axis the user feels the clusters and the voids of the distribution.

Finally, the actuation can enable *joystick*-style interactions, see Fig. 1f. These interactions afford the impression of pushing beyond the ends of the sliders, giving the haptic sensation of a 'rock-over' interaction. This allows the user to expand the data range that the sliders represent (e.g. zoom out). We achieve this by very quickly and repeatedly pushing back against the user as they push the slider beyond the end of the sliders' range.

Follow mode – The sliders' actuation also allows for automation of slider position - Figs. 2a-c. We term a number of behaviours where one slider position automatically follows the position of another slider "follow mode". Basic follow mode allows for one slider to follow the other by a fixed offset d. For example, in single value (rather than range) selection operations, it can be useful to set $d = 0$ such that the two sliders are tied to the same value (*discrete follow-mode* - 2a), creating the appearance of a single slider. Alternatively, a fixed d can be kept between the two sliders, creating a *range follow mode*, for example to pan a constant width window - 2b. Finally, the sliders may be set to arbitrary positions, for example, to restore a previous range selection when remapping the data binding of the axis, or if multiple MADE-Axes are mapped to one dimension (for example during multiuser operation) any slider changes on one axis should be reflected on the other (*ghost follow mode* - 2c).

Zoom Operations: The MADE-Axis sliders can represent any range of data - Figs. 2d-f. At their most intuitive, the slider extent covers the full range of the data dimension to which it is bound and pinching the sliders together causes the display to zoom to the selected extent, 2d. However, the user may require more precision in performing range selections, so pressing the button causes the sliders to jump back to their end positions, mapping the new selection range to the full travel of the sliders without changing the visual, 2e. Upon completion, joystick-mode can enable the user to zoom back out, past the zoomed extent, 2f.

3.2.1 Composability. Multiple MADE-Axes can be used simultaneously, limited only by Bluetooth connectivity (in Use Case 5.2.2 we test with six). These may be combined in various modes of operation, with or without tracking, in mixed-reality or in tandem with a screen.

In-situ Operation – The Embodied Axis device [11], which inspired MADE-Axis, involved three sets of sliders fixed in position orthogonally with respect to each other and was anchored to a table. By contrast, MADE-Axes can be placed to align directly with the spatial dimensions of a visualisation for use with either a conventional display device or mixed-reality. Their mapping to a data dimension can be fixed (for example, selected with the rotary control) and they can be placed by the user in a position that makes sense (e.g. aligned to the visualisation's spatial mapping) or is convenient or ergonomic, e.g. see Use Case 5.1.

Tracked Operation – Alternately, the MADE-Axis may be spatially tracked and the data binding can be determined from orientation (horizontal for x-axis, vertical for y-axis) or proximity (bind

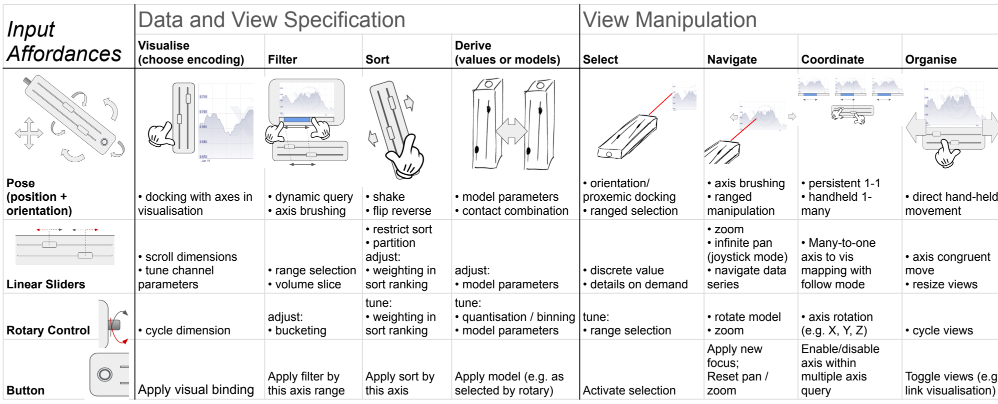


Fig. 3. Interactive Dynamics for MADE-Axis Input Affordances

to closest visual axis) relative to the visualisation, e.g. see Use Case 5.2.1. Alternately, if there are as many MADE-Axes as dimensions in the dataset, then there is no need for remapping, and the persistent 1:1 mapping of MADE-Axes to data dimensions becomes a complete physical embodiment of the dataset, e.g. see Use Case 5.2.2.

4 MAPPING MADE-AXES AFFORDANCES TO INTERACTIVE DYNAMICS FOR VISUALISATION

Here, we explore the interaction space of MADE-Axes, in light of Heer and Shneiderman's taxonomy of interactive dynamics for visual analysis [27]. Their taxonomy is divided into three high-level task types: *Data and View Specification*; *View Manipulation*; and *Process and Provenance*. We explore how MADE-Axes, either individually or in combination, can support each task. The goal is to reflect on the interaction modalities proposed in earlier sections and extend these to demonstrate the concordance of the MADE-Axis hardware design with the full range of interaction dynamics.

When considering the interaction design space of the MADE-Axes, we organise the affordances for interaction into three basic dimensions: *Input*, *Output* and *Composability*. In particular, the *Input* dimension of MADE-Axis is well aligned to lower-level dynamics of *Data and View Specification* and *View Manipulation* and we give a complete summary mapping for these in Fig. 3, with each entry described further in the text below.

4.1 Data and View Specification

Visualise (Choose Encoding) – MADE-Axis offers multiple ways to bind its control to data dimensions from the visualisation. Simplest is through explicit choice of encoding via rotary or slider browsing of available data dimensions. For example, in the setup for our time series visualisation (Use Case 5.1) the two MADE-Axes are each mapped to the *time* and *country* dimensions by rotary cycling through the available dimensions in the dataset and rotary click to select.

Alternately, pose may be used to automatically bind dimension by "docking" MADE-Axis with an axis of the visualisation by manual placement. Orientation may be sufficient, for example given a visualisation with two orthogonal spatial dimensions (x, y) a MADE-Axis can be bound to each by orientation (horizontal or vertical) on a flat surface. A third spatial dimension could be bound by standing the MADE-Axis upright on the table. In a visualisation with multiple spatial dimensions (e.g. parallel coordinates), proximity of the MADE-Axis to the axis visual may be more appropriate (as per Use Case 5.2.1). Fine control of visual channel parameters is facilitated by MADE-Axis

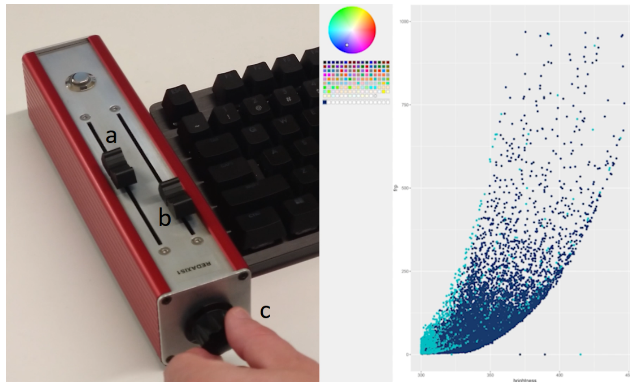


Fig. 4. Choosing colour encoding. Manipulating the colour channel in HSV space: a - left slider: Value; b - right slider: Saturation; c - rotary encoder: Hue.

inputs. For example, Fig. 4 demonstrates remapping the colour encoding of a data series, which works particularly well in HSV colour space mapping saturation and value to sliders and the rotary encoder to the cyclical Hue dimension.

Filter – Filtering data to a restricted **range** with the sliders is the most obvious example of filtering support. In volumetric displays, such as medical scan data, the result of such filtering is a volume slice. However, in Use Case 5.2.2, we demonstrated more sophisticated narrowing of the data via **dynamic queries** through composition of multiple MADE-Axes. That is, when multiple MADE-Axes are brought together to create a single visualisation, the set of data shown is the logical AND of the ranges set for each. **Axis Brushing** is a very light-weight example of dynamic queries explored in Use Case 5.2.1. There, hand-held MADE-Axis may be "brushed" against other individual axes, or axes composed in the environment into visualisations. As they come close visual links appear between the axes, providing a facility to quickly explore how the values of the data points within the selected range on the current axis align with those in the target.

Sort – The physical embodiment of an axis suggests obvious natural embodied **pose** interactions for actions like sorting. **Flipping** the axis, such that the end corresponding to minimum and maximum are reversed, naturally reverse the ordering. Similarly, **Shaking an axis** suggests forcefully organising the data by the corresponding data dimension. Sliders can **restrict** the range of a sort, or a slider can control a **partition** interaction, whereby a slider can be used to select an element which becomes a pivot for the partitions. A more complicated sort across an ordering function combining multiple dimensions can also be embodied by a set of MADE-Axes, where the weighting of the dimension corresponding to each MADE-Axis can be adjusted by **pose**, **slider position**, or fine-tuned with the **rotary encoder**.

Derive – Similar to the ordering functions described above, MADE-Axis *input* affordances can be used to manipulate derived data, for example, the **weighting** of different data-dimensions' contributions to a linear or non-linear model fitting of multidimensional data could be controlled through MADE-Axis relative pose of each MADE-Axis or slider position. Similarly, relative position can be used to combine data dimensions, e.g. we could extend Use Case 5.2.2 such that the *horsepower* dimension could be divided by *weight* by placing the first above and in contact with the latter. The rotator knob can then be used to tune multipliers for each of these in the derived result. Actuation is another important affordance to support derived data or features inferred from analysis. For example *notching* can be used to highlight, quantised binning, the mean and quartiles or extrema in the data as demonstrated in Use Case 5.1.

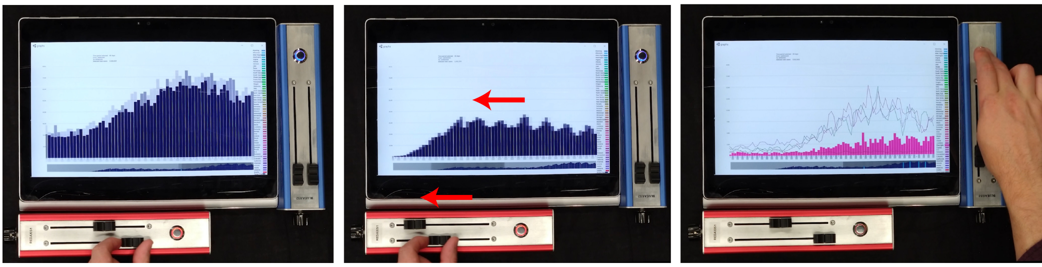


Fig. 5. Use with a 2D chart visualisation with a tablet display: left - range selection (min,max); middle - range sliding to left; right - adding a state to the selection.

4.2 View Manipulation

Select – Range selection with sliders and fine rotary encoder control is discussed at length across the use-cases in Section 5. More nuanced control of selection is provided by haptic snapping to data features, such as extrema or value bins as described in *Derive*. In Use Case 5.2.2 we demonstrated a **details on demand** feature using follow mode on one MADE-Axis to quickly navigate the points in the dataset and display an infobox.
Navigate – **Axis brushing** helps to quickly find interesting features in the data; **zoom and pan** operations were discussed in 3.2; the axis-aligned rotary encoders are useful for rotating volumetric data in the axis aligned with the MADE-Axis. ***Coordinate*** – MADE-Axis can map to data dimensions either 1-1 (Use Case 5.2.2 or 1-many (Use Case 5.2.1), or multiple MADE-Axis to a single dimension. In the latter case, **Actuation** and **Follow Mode** is key for coordinating activity between users manipulating the same datasets (e.g. in a VR context). ***Organise*** – With tracking visualisations may be organised by direct hand-held controller-couple movement, or indirect 'beam' manipulation. Sliders can be used to perform axis congruent movement or scaling of visuals. Encoder can be used to cycle views or data series (as in 5.1).

4.3 Process and Provenance

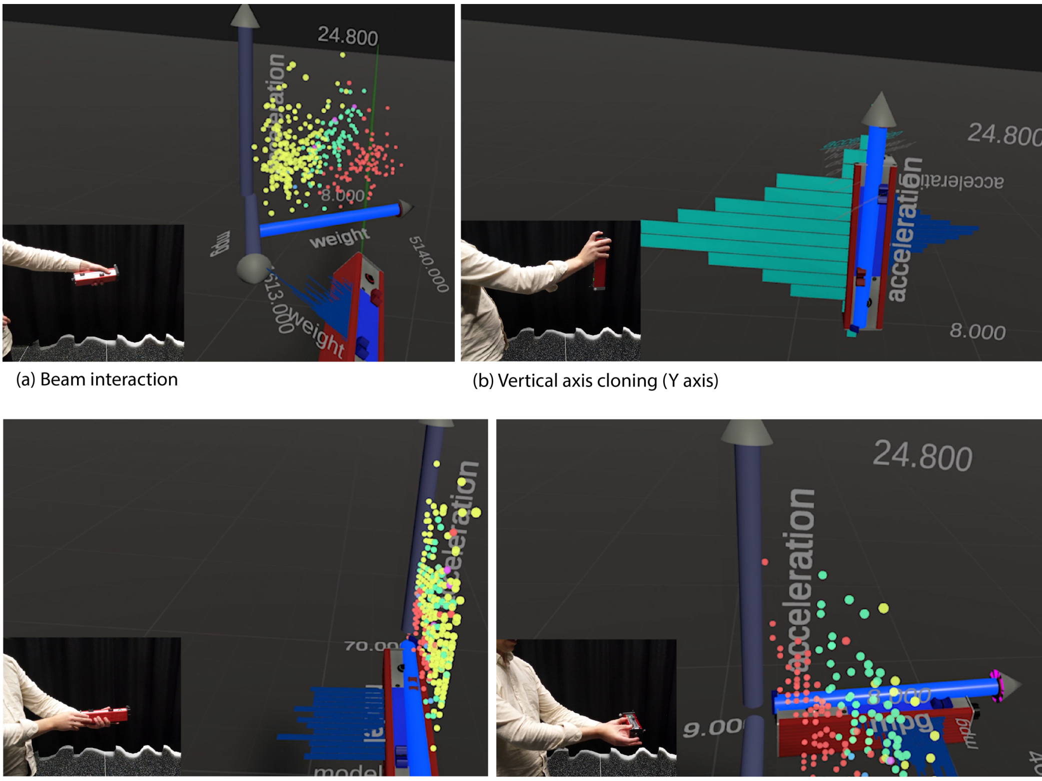
MADE-Axis are designed primarily to support the kind of low-level data visualisation analysis tasks described above, however, aspects of their design do support process and provenance. In particular, **actuation** allows for user-controlled haptic marking of key data features discovered during analysis. Sliders can be moved to the range selections or recorded marks of others to assist shared data understanding. Haptic features discussed in 3.2 can also be used in guidance scenarios to inform users of data features discovered by algorithms.

5 USE CASES

We describe three scenarios for MADE-Axis use, spanning traditional data visualisation and immersive analytics setups.

5.1 Screen-based Time Series Visualisation

Our first example demonstrates the coupling of MADE-Axes to a standard 2D time-series visualisation (of daily COVID-19 cases in different US states). We use two controllers laying flat in the plane of the (external) display: one horizontal with respect to the user's point of view; and one laying vertically (away from) the user. It is natural, then, to bind the horizontal MADE-Axis to the x-axis of the visualisation (date), and the vertical one to y-axis.



(a) Beam interaction (b) Vertical axis cloning (Y axis)

(c) Horizontal axis cloning (X axis) (d) Depth axis cloning (Z axis)

Fig. 6. The MADE-Axis used as a controller for ImAxes.

This coupling allows for basic selection of minimum and maximum values to zoom in on the x-axis (time), Fig. 5-left. The push button locks the range such that dragging either slider moves the range window left or right without resizing (using Range Follow Mode, see Sec. 3.2 and Fig. 5-middle). In this scenario, the rotary click is used to add and remove haptic markers on individual dates. This allows the user to retrieve particular insights while exploring the data (see Section 4.3). The y-axis lets the user select US states. Since the data dimension is discrete the slider is notched with one notch for each state. The state currently selected by the slider is shown as a bar chart. A push on the top button of the y-axis controller (Fig. 5-right) adds the current selected state as a line chart so the user can compare the evolution of the spread with the other selected states. The rotary wheel on the controller attached to the y-axis applies a logarithmic step zoom in and zoom out to the selected charts making it easy to compare trends between states with greatly varying total numbers.

5.2 Immersive Data visualisation [VR/AR]

5.2.1 Hand-held controller. MADE-Axis can be used as a hand-held controller for immersive, multidimensional data visualisation. In the VR ImAxes system [14], data dimensions are embodied in manipulable, virtual 3D axes visuals that the user grabs with standard VR controllers and arranges in specific layouts to create visualisations. With the help of optical tracking (e.g. a Vicon tracker system) the MADE-Axis can be used as a 6DoF handheld VR controller with controls that directly map to the specific needs of interaction with data visualisations.

While holding the MADE-Axis, the user can use it as an indirect pointer controller, i.e. point the beam emerging from the top of the device at an axis and select it with the top button, Fig. 6a. They can then move the controller while holding down the button to drag the axis lateral to its view plane; or remap the data dimension of the axis using the rotary encoder; or adjust range filtering using the sliders.

Alternately, while the beam is not coinciding with any existing axis in the scene, they can click the button to instantiate a new axes (axis cloning) at the position and orientation of the MADE-Axis in their hand, Fig. 6b-d. As long as the button is held down the new axis will follow the controller position until the button is released. In this mode, as before, they can also remap the data dimension with the rotary encoder or adjust range filtering with the sliders.

In this scenario, when a different axis is selected the actuated sliders automatically move to match the filter state of that axis. For example, when the user docks a new virtual embodied axis to the MADE-Axis the previous filters are applied on the device (the motors activate the slider knobs to match the virtual axis).

This scenario illustrates how the pose of the tracked MADE-Axis and its physical controls are used as **input** for interactive visualisation interactions (pointer, docking, range selection and filtering, dimension navigation). It also illustrates the actuation of the sliders as an **output** for feedback.

5.2.2 One-to-one MR embodiment of multiple dimensions. While the previous example used a single MADE-Axis to manipulate many data axes in a VR scene, it is also possible to use multiple MADE-Axes in a single application, for example, to allow multiple users to each have their own MADE-Axis, or (as in this example) to have a MADE-Axis permanently mapped to each dimension in the data set. In this scenario, multiple users, each wearing a Microsoft Hololens 2 AR headset, work with six MADE-Axes arranged on a table. Visuals are generated depending on the poses of the MADE-Axes, again, following the ImAxes spatial grammar [14].

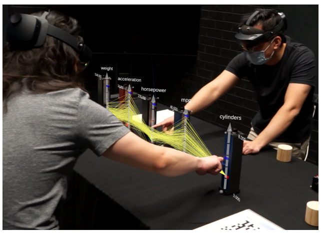
In this scenario there is a permanent one-to-one mapping between each of the six data dimensions and each MADE-Axis. As before, the sliders apply range filtering to the set of data marks shown – the button toggles follow mode, such that an infobox is shown for the data point at the position of the slider (i.e. details on demand).

This setup leverages a natural, physical and tangible space that promotes collaborative visualisation [32]. The MADE-Axes can be placed flat on the table surface or stood vertically on the table to create 3D visualisations. The users can peer around the table, and physically manipulate and arrange their views during their data exploration process.

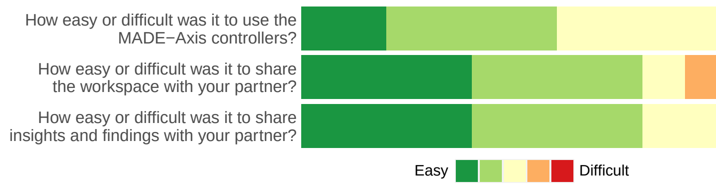
6 USER STUDY: EMBODIED AXES

We explored how people used MADE-Axes for data visualisation and analysis in the Mixed Reality embodied setup described in Section 5.2.2. We designed a study for pairs of participants who were tasked with analysing multivariate data in a collaborative tabletop environment[1]. We chose to use a tabletop because (1) it is a common and well established collaborative setup [32], and (2) it lends itself well to placing multiple MADE-Axes on top of it. Our primary goal was to identify interesting behaviours and patterns in how users use a device like the MADE-Axis, rather than measuring performance and accuracy.

[1]The study was conducted with proper COVID-19 safety procedures as per guidelines from our university and state government. Participants wore face masks and therefore were not required to socially distance during the study.



(a) The physical setup of our study



(b) Post-study Likert-scale responses from the 10 participants

Fig. 7. Study setup: six MADE-Axes and six wooden block for propping up and aligning the MADE-Axes. Vicon tracking cameras are mounted overhead to track the positions of the MADE-Axes. Participants can freely move around the table (a); and qualitative feedback summary

6.1 Experimental Set-up

Both participants in each group wore a HoloLens 2 augmented reality headset, and stood around a table which measured 180 cm by 90 cm and was 90 cm high. Six MADE-Axes were placed on the table at the beginning of each session, with a set of six wooden blocks placed on the edge that could be used to prop up and align the MADE-Axes. The MADE-Axes were tracked using a Vicon Motion Tracking System with eight cameras mounted overhead. Reflective markers were mounted on both ends of the MADE-Axes. We aligned the coordinate systems of the HoloLens 2 headsets and the Vicon system using a QR code. This provided a synchronised position in 3D space, which we used to accurately align the virtual axis objects. The HoloLens 2 headsets were only used as observers, with any spatial awareness or hand gesture functionality being disabled. The final physical setup is shown in Figure 7a.

6.2 Study Design

We use the Auto MPG data set sourced from the UCI Machine Learning Repository [18] due to likely familiarity of participants with this topic. We only included six of the nine original dimensions (*mpg*, *cylinders*, *horsepower*, *weight*, *acceleration*, *name*) in order to establish a strict one-to-one mapping between the six data dimensions and the six MADE-Axes. To maximise the sensation of embodiment between data dimension and MADE-Axis, we excluded any functions which would allow participants to change which dimension a MADE-Axis was mapped to.

We conducted the study with participants in groups of two. After an initial study briefing and demographics questionnaire, the pairs were trained in the use of the MADE-Axis, as well as how to construct parallel coordinates plots and 2D and 3D scatterplot visualisations. Participants were not taught how to construct more complex visualisations such as scatterplot matrices. As the aim of the study was to observe how participants collaboratively analyse data, we gave them a series of questions to prompt their exploration:

- What is the name of the fastest car in the dataset?
- Do cars that are faster and/or more powerful have better or worse fuel efficiency (i.e., *mpg*)?
- How does the number of cylinders a car has typically affect its other characteristics? Are there any exceptions to these findings?
- If time permits, find any other interesting trends, relationships, or outliers in any part of the data you wish

The questions were printed on two A4 sheets of paper that were handed to the participants. Some questions were intentionally vague in order to promote further exploration of the data. We gave

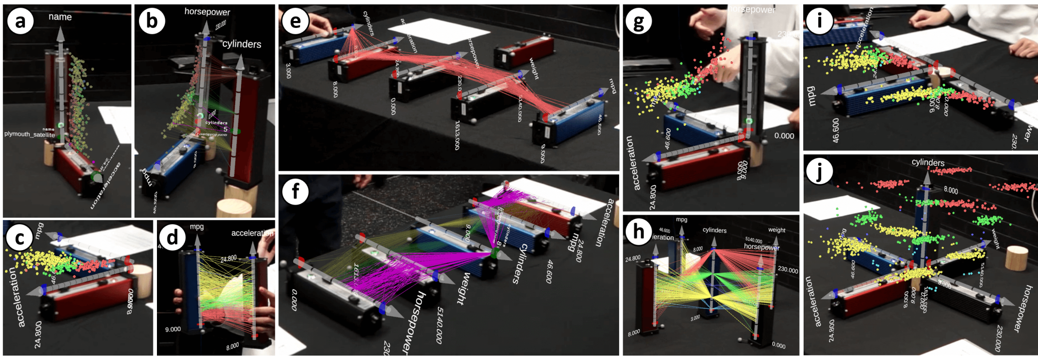


Fig. 8. Visualisations constructed by study participants with MADE-Axis: (a, b, c, d) examples of 2D visualisations, (e) parallel coordinates plot (PCP) with filtered items using sliders, (f) PCP with selected items (highlighted in purple) and non-selected items (semi-transparent), (g, h) examples of 3D visualisations, (i, j) 3D scatterplot matrices with shared data axes.

no explicit instruction in how participants should perform the tasks. Participants were given a post-study questionnaire to answer individually. It asked Likert-scale and open-ended questions about how easy it was to use the MADE-Axis, how easy it was to share insights and the workspace, and their opinions on the data visualisation system as a whole. The duration of each session was approximately 80 minutes.

6.3 Participants

We recruited 10 participants (2 female and 8 male) from our university aged between 18 and 44 years, forming five groups. Three groups were all PhD students or researchers who were experienced in data visualisation and/or virtual reality (referred to as groups G1, G2, G3, and participants P1 to P6). Two groups were undergraduate or masters students in non-computer science nor data visualisation fields (referred to as G4 and G5, and participants P7 to P10). For these two groups, we took additional time to explain visualisation concepts such as parallel coordinates. Six participants had little to no experience with AR. All participants self-reported either 4 or 5 for how well they knew their group-mate (1: strangers, 5: good friends).

6.4 Results

Orientation of 2D visualisations – Figure 8 shows a selection of the many different visualisations that study participants constructed. Groups used mostly 2D visualisations, with more parallel coordinate plots (PCPs) created than scatterplots. There was no overall preference of how these 2D visualisations were oriented: G1 used only horizontal visualisations (i.e., flat on the table), G4 and G5 used only vertical visualisations (i.e., perpendicular to the table), and G2 and G3 mixed the two. Those who created vertical visualisations made frequent use of the wooden blocks, usually to prop up the perpendicular axis of scatterplots (Figure 8a). There were also other uses of the blocks: G4 placed a block under a single MADE-Axis that was linked to a scatterplot to level out their heights (Figure 8b), and G3 used it to accurately space out and align the MADE-Axes on a horizontal scatterplot (Figure 8c). While vertical visualisations forced participants to crouch slightly, this did not seem to cause any issues. While lifting up the MADE-Axes to head height would have prevented this, P5 was the only participant to do so when analysing a single parallel coordinates visualisation (Figure 8d).

2D parallel coordinate plots – All groups created simple PCPs consisting of two or three axes, while three groups created larger or more complex two-dimensional PCPs to identify trends between five of the six data dimensions. Interestingly, while G1 and G5 used the sliders to filter the categorical *cylinders* dimension (Figure 8e), G2 instead used the sliders in details-on-demand mode to do so (Figure 8f), ultimately achieving a similar result. The MADE-Axes were frequently rearranged to find correlations between different data dimensions.
3D visualisations – All groups created three-dimensional visualisation, which often required participants to physically move to view visualisations from different angles by walking around the table and leaning forward. We observed that groups who created 3D scatterplots (Figure 8g) only used them for brief moments of time, either then trying another visualisation idiom due to perception issues (G5, G3), or using them only to double check their findings (G2). In contrast, three-dimensional PCPs were used extensively by two groups (G5, G3) (Figure 8h). Both groups placed the *cylinders* dimension at the center of the PCP, such that they could filter and inspect the *cylinders* variable and see the effect on all other variables. Interestingly, G5 had no data visualisation background but were still able to construct and properly analyse their three-dimensional PCP. The same two groups also created many of the more 'exotic' visualisations such as scatterplot matrices (Figure 8i and 8h), although this was to overcome the restriction of the fixed mapping of one attribute to one embodied MADE-Axis. In the case of G5, they had attempted to create four vertical 2D scatterplots stemming from the same categorical vertical axis, but accidentally created a 3D scatterplot matrix. (Figure 8j).
Collaborative use of the table – After constructing visualisations with the MADE-Axes, groups would rarely move or re-position them. Instead, they would either swap MADE-Axes in and out of their existing visualisation depending on the data dimensions they needed, or completely tear down the visualisation to create a new one. No groups had constructed and analysed two or more visualisations simultaneously; all groups were always focused on a single visualisation. All pairs took turns in interacting with the MADE-Axes, with no single participant dominating the interaction nor the analysis. Groups did not necessarily need to make physical space for each other to reach the MADE-Axes, especially so for G4 and G5 who both spent significant amounts of time at different sides of the table.

6.4.1 Participant Feedback. Figure 7b shows Likert-scale responses from the 10 participants given during the post-study questionnaire. Participants generally rated MADE-Axis as being easy to use during the study. Similarly, most participants found that it was easy to share the workspace and to share findings with their partner.

Below we report on open-ended feedback provided by study participants, categorized into three high level themes.
Embodied MADE-Axes as a visualisation system – Seven participants specifically praised the overall visualisation system as being easy to use and discover insights with, that it was *"quite reactive to what we were trying to do and did not feel too limiting to what we were trying to do with it"* [P9] and that it was *"very easy to swap between different combination of dimensions to see the high level correlation or high level exceptions of the dataset"* [P4]. It is notable that four of these seven participants did not have data visualisation backgrounds, yet also stated they were able to take full advantage of the system. This is because it was *"more intuitive so [I could] get a hang of the controllers compared to having to learn Excel functions"* [P7] which made them *"[feel] like I immediately had a high degree of control over how I visualised the data, despite never having experienced this system before"* [P10]. However, four of the 10 participants reported that it took some time to familiarise themselves with the system. Even so, this did not appear to be significantly long, as one participant

stated that *"it took some time to get used to, but given a few minutes to adapt... there was a lot of good ways to find info based on the graphs given"* [P7].

Embodied MADE-Axes as an interaction device – Seven participants reported that having tangible input via the MADE-Axis made exploring the data easier and more enjoyable, making *"the experience feel like a real-life interaction"* [P3]. The use of AR also made them feel comfortable sharing findings with each other, as *"you can see your partner and speak directly with them"* and *"the fact that the tangible/physical object [is] present in front of [you] (as opposed to virtual ones), made me more confident when communicating my thoughts and findings to my partner"* [P5]. Many participants called out several usability issues of the MADE-Axis however, such as: the controller being a bit heavy and fatiguing (P2, P9, P5); poor placement of buttons and sliders on the MADE-Axis making it *"slightly awkward to use"* [P9]; fragility due to the Vicon reflective markers (P9, P10); lack of visual feedback between toggle modes (P1); and incomplete modularity due to the need for the separate wooden blocks (P7). Two participants (P3, P5) suggested there should be an option to re-assign the data dimension mapping for each MADE-Axis, which, as explained above, is a possible functionality of MADE-Axis that we decided to exclude for this user study. While we chose not to ask about embodiment, two participants went out of their way to state that *"[interacting] with the controllers feels like [interacting] with the virtual axes directly"* [P2] and *"it feels like you are more immersed and [can] directly interact with the data using the physical controller"* [P3].

Embodied MADE-Axes as a collaborative system – Five participants highlighted their ability to easily work and share their findings with each other. This was for two main reasons: interacting with the MADE-Axis was easy enough such that *"communicating did not require any use of jargon or terms my partner could not understand"* [P7] and they could *"[easily] share information and findings with a partner who is in the same environment because both users are viewing the same things"* [P9]. This shared vision was particularly helpful as participants could simply *"point to the view or any data on the plots to share insights"* [P2]. However, a slight misalignment of the visualisation positions between the two HoloLens headsets made it so that *"when pointing at one certain area, [it was] a little difficult to tell if we [were] talking about the same thing"* [P6]. In contrast to this benefit of shared vision, two participants commented that additional physical movement was required as they needed to *"move aside to allow [my partner] to see it from [my] perspective"* [P9]. This is potentially exacerbated by the need to physically move around in order to properly view certain visualisations, particularly three-dimensional ones. Four participants said this was something they continuously had to manage during the experiment, but one of them also noted that *"when we are sharing with two people it should be fine, but with more people, it will be more difficult"* [P3]. While participants found tightly-coupled collaboration to be well supported, two participants criticised the inability for loosely-coupled collaboration. This is likely also due to the fixed one-to-one mapping of attribute dimensions to devices, whereby *"two participants cannot do filtering at the same time with different purposes"* [P1] and *"we only have one axis for each dimension, which means I need to share my workspace with my partner"* [P2].

7 DISCUSSION

We now discuss the limitations of our study and reflect on the possibilities offered by the design of MADE-Axes and its potential improvement.

Study limitations – Past work has focused on studying how tangible sliders can improve performance in data exploration. Our study focused on observing how the MADE-Axes are composed and organised in space collaboratively by using the specific spatial grammar of *ImAxes* [14]. To validate the potential of MADE-Axes we focused our controlled experiment on a single dataset and a set of visualisation paradigms. Other visualisation paradigms and datasets should be explored to fully understand the potential use of the MADE-Axes. In particular it would be useful to understand how such controllers could help explore scientific data that have true positional 3D spatial encoding and that necessitate specific interactive tasks to be supported to allow thorough analysis [5].

Further, our study sought to validate MADE-Axes for exploratory analyses. Going forward it would be worthwhile to compare MADE-Axes support for very specific analysis tasks against other possible modes of interaction in an empirical study. In particular, comparing MADE-Axes with classical VR controllers in a controlled experiment would help highlight the benefits and limitations of our device. Additionally, our study did not specifically focused on quantifying the benefits of modularity of the axes to explore data; more work is needed in the future to measure the impact of tangible modularity of axes for this task.

Promoting collaboration and visualisation literacy – Past work has highlighted the potential of tangible devices to foster collaboration [52, 53]. Yet, collaboration is rarely studied [59] in AR visualisation contexts. Our study results helped us confirm the benefits of tangible devices in such contexts [58]: MADE-Axes helped participants to easily work and share findings with each other.

The use of physical building blocks to create visual representations has been praised in prior work for its potential to help educate people about data and visual representations [30, 42]. In our study, we confirmed that participants, even with minimal knowledge in visualisation, gathered insights about the dataset and created a wide variety of visualisation ranging from 2D scatterplots to more advanced 3D parallel coordinates. In addition to facilitating the creation of complex visual representations, MADE-Axes can also further motivate users to explore data and different visualisations. Tangible controllers indeed give a better sense of *personal agency*[15, 42], that is a feeling that they have done something in contrast to watching a system do something. Past research seems to suggest that personal agency could benefit non-expert users in visualisation contexts [39]. We can posit that the feeling of personal agency is even reinforced by the possibility offered to construct visualisation. This feeling of personal agency combined with the inherent entertaining value of tangibles [3, 70] is thus very likely to promote more playful and meaningful exploration of data and therefore could help increase visualisation literacy.

Hardware and design improvements – One of the main limitations of the MADE-Axes is their size. While they afford a comfortable composable "brick" to build visualisation in a Mixed-Reality scenario, they are not optimal for hand-held interaction (multiple participants reported feeling that the controllers were too heavy). With constant improvement on miniaturisation of components and lighter materials for cases, we assume that a future generation of MADE-Axes could be thinner, lighter and better suited for handheld controller scenarios. Another limitation with our setup is the need for an optical tracker for accurate pose tracking. An obvious improvement to the device would be to provide on-board, inside-out optical positioning. Of course, this would mean the device would require significantly more computational power than it currently has - but as such positioning becomes more common in commodity devices (such as common VR and AR headsets) we expect the additional hardware and sensor cost to rapidly reduce. Further optimisations in power consumption, as well as alternative enclosure designs, seeking weight reduction and further ergonomic improvements could also be investigated.

The current design of the MADE-Axes includes the basic affordances of an embodied data axis. Our design focused on creating a tangible system to build visualisations that use a Cartesian coordinate system (i.e., defined by 2D and 3D orthogonal or parallel axes). Hence we used linear sliders that eventually dictated the form factor of the device; however further geometries could be explored for different coordinate systems. Furthermore, the controls are currently limited to sliders, rotary knobs and push buttons. Additional controls to provide more physical affordances for interactive data exploration provide a tremendous avenue for research. Future work could, for instance, focus on how to extend our design to provide affordances for data queries on textual information.

8 CONCLUSION

In this paper we presented the design and the evaluation of the MADE-Axis, a novel controller for embodied interaction with multivariate data. We demonstrated the use of MADE-Axes in both traditional non-immersive and immersive visualisation setups. After presenting a variety of use cases and deriving a design space of interaction, we studied how the MADE-Axes are used in a mixed-reality collaborative setup to explore data. We observed that our mixed-reality system was effective for visualisation tasks, and that participants with minimal knowledge in visualisation were able to gather insights about the data. We observed that participants created a wide variety of visualisations on the table, ranging from basic 2D scatterplots to more advanced 3D parallel coordinates. We also observed that the tangibility of the controller promoted discussions between the collaborators and facilitated discussions of insights.

We feel the embodiment of data axes provides an intuitive and discoverable user interface for visualisation. The basic input elements (sliders, buttons, pose of the controller) are simple but in combination allow for rich exploration of the data. Going forward, we are encouraged that the design and form-factor is a good basis for interactive data visualisation and we look forward to refining the device and exploring further use cases.

REFERENCES

[1] A. Batch, A. Cunningham, M. Cordeil, N. Elmqvist, T. Dwyer, B. H. Thomas, and K. Marriott. 2020. There Is No Spoon: Evaluating Performance, Space Use, and Presence with Expert Domain Users in Immersive Analytics. *IEEE Transactions on Visualization and Computer Graphics* 26, 1 (2020), 536–546. https://doi.org/10.1109/TVCG.2019.2934803

[2] Lonni Besançon, Paul Issartel, Mehdi Ammi, and Tobias Isenberg. 2017. Hybrid Tactile/Tangible Interaction for 3D Data Exploration. *IEEE Transactions on Visualization and Computer Graphics* 23, 1 (Jan. 2017), 881–890. https://doi.org/10.1109/TVCG.2016.2599217 **OA available**.

[3] Lonni Besançon, Paul Issartel, Mehdi Ammi, and Tobias Isenberg. 2017. Mouse, Tactile, and Tangible Input for 3D Manipulation. In *Proc. CHI*. ACM, New York, 4727–4740. https://doi.org/10.1145/3025453.3025863 **OA available**.

[4] Lonni Besançon, Mickael Sereno, Lingyun Yu, Mehdi Ammi, and Tobias Isenberg. 2019. Hybrid Touch/Tangible Spatial 3D Data Selection. *Computer Graphics Forum* 38, 3 (June 2019), 553–567. https://doi.org/10.1111/cgf.13710 **OA available**.

[5] Lonni Besançon, Anders Ynnerman, Daniel F Keefe, Lingyun Yu, and Tobias Isenberg. 2021. The State of the Art of Spatial Interfaces for 3D Visualization. *Computer Graphics Forum* (2021). https://doi.org/10.1111/cgf.14189

[6] Verena Biener, Daniel Schneider, Travis Gesslein, Alexander Otte, Bastian Kuth, Per Ola Kristensson, Eyal Ofek, Michel Pahud, and Jens Grubert. 2020. Breaking the Screen: Interaction Across Touchscreen Boundaries in Virtual Reality for Mobile Knowledge Workers. *IEEE Transactions on Visualization and Computer Graphics* 26, 12 (2020), 3490–3502. https://doi.org/10.1109/TVCG.2020.3023567

[7] Simon Butscher, Sebastian Hubenschmid, Jens Müller, Johannes Fuchs, and Harald Reiterer. 2018. *Clusters, Trends, and Outliers: How Immersive Technologies Can Facilitate the Collaborative Analysis of Multidimensional Data*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173664

[8] Alvaro Cassinelli and Masatoshi Ishikawa. 2009. Volume slicing display. In *SIGGRAPH ASIA Art Gallery & Emerging Technologies*. 88. https://doi.org/10.1145/1665137.1665207 **OA available**.

[9] Marco Cavallo, Mishal Dolakia, Matous Havlena, Kenneth Ocheltree, and Mark Podlaseck. 2019. Immersive Insights: A Hybrid Analytics System ForCollaborative Exploratory Data Analysis. In *25th ACM Symposium on Virtual Reality Software and Technology* (Parramatta, NSW, Australia) *(VRST '19)*. Association for Computing Machinery, New York, NY, USA, Article 9, 12 pages. https://doi.org/10.1145/3359996.3364242

[10] Jarry HT Claessen and Jarke J Van Wijk. 2011. Flexible linked axes for multivariate data visualization. *IEEE Transactions on Visualization and Computer Graphics* 17, 12 (2011), 2310–2316.

[11] Maxime Cordeil, Benjamin Bach, Andrew Cunningham, Bastian Montoya, Ross T Smith, Bruce H Thomas, and Tim Dwyer. 2020. Embodied Axes: Tangible, Actuated Interaction for 3D Augmented Reality Data Spaces. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–12.

[12] Maxime Cordeil, Benjamin Bach, Yongchao Li, Elliott Wilson, and Tim Dwyer. 2017. Design space for spatio-data coordination: Tangible interaction devices for immersive information visualisation. In *2017 IEEE Pacific Visualization Symposium (PacificVis)*. IEEE, 46–50.

[13] M. Cordeil, B. Bach, Yongchao Li, E. Wilson, and T. Dwyer. 2017. Design space for spatio-data coordination: Tangible interaction devices for immersive information visualisation. In *2017 IEEE Pacific Visualization Symposium (PacificVis)*. 46–50. https://doi.org/10.1109/PACIFICVIS.2017.8031578

[14] Maxime Cordeil, Andrew Cunningham, Tim Dwyer, Bruce H. Thomas, and Kim Marriott. 2017. ImAxes: Immersive Axes as Embodied Affordances for Interactive Multivariate Data Visualisation. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 71–83. https://doi.org/10.1145/3126594.3126613 **OA available**.

[15] David Coyle, James Moore, Per Ola Kristensson, Paul Fletcher, and Alan Blackwell. 2012. I did that! Measuring users' experience of agency in their own actions. In *Proceedings of the SIGCHI conference on human factors in computing systems*. 2025–2034.

[16] Gerwin de Haan, Michal Koutek, and Frits H. Post. 2002. Towards Intuitive Exploration Tools for Data Visualization in VR. In *Proc. VRST* (Hong Kong, China). ACM, New York, 105–112. https://doi.org/10.1145/585740.585758 **OA available**.

[17] Paul Dourish. 2001. *Where the action is.* MIT press Cambridge.

[18] Dheeru Dua and Casey Graff. 2017. UCI Machine Learning Repository. http://archive.ics.uci.edu/ml

[19] Barrett Ens, Benjamin Bach, Maxime Cordeil, Ulrich Engelke, Marcos Serrano, Wesley Willett, Arnaud Prouzeau, Christoph Anthes, Wolfgang Büschel, Cody Dunne, Tim Dwyer, Jens Grubert, Jason H. Haga, Nurit Kirshenbaum, Dylan Kobayashi, Tica Lin, Monsurat Olaosebikan, Fabian Pointecker, David Saffo, Nazmus Saquib, Dieter Schmalstieg, Danielle Albers Szafir, Matt Whitlock, and Yalong Yang. 2021. *Grand Challenges in Immersive Analytics.* Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3411764.3446866

[20] George W Fitzmaurice. 1996. *Graspable User Interfaces.* Ph.D. Dissertation. University of Toronto, Canada. http://www.dgp.toronto.edu/~gf/papers/PhD%20-%20Graspable%20UIs/Thesis.gf.html **OA available**.

[21] Sean Follmer, Daniel Leithinger, Alex Olwal, Nadia Cheng, and Hiroshi Ishii. 2012. Jamming User Interfaces: Programmable Particle Stiffness and Sensing for Malleable and Shape-Changing Devices. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology* (Cambridge, Massachusetts, USA) *(UIST '12)*. Association for Computing Machinery, New York, NY, USA, 519–528. https://doi.org/10.1145/2380116.2380181

[22] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. InFORM: Dynamic Physical Affordances and Constraints through Shape and Object Actuation. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology* (St. Andrews, Scotland, United Kingdom) *(UIST '13)*. Association for Computing Machinery, New York, NY, USA, 417–426. https://doi.org/10.1145/2501988.2502032

[23] Travis Gesslein, Verena Biener, Philipp Gagel, Daniel Schneider, Per Ola Kristensson, Eyal Ofek, Michel Pahud, and Jens Grubert. 2020. Pen-based Interaction with Spreadsheets in Mobile Virtual Reality. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 361–373. https://doi.org/10.1109/ISMAR50242.2020.00063

[24] Steven R. Gomez, Radu Jianu, and David H. Laidlaw. 2010. A Fiducial-Based Tangible User Interface for White Matter Tractography. In *Advances in Visual Computing*. Springer, Berlin, Heidelberg, 373–381. https://doi.org/10.1007/978-3-642-17274-8_37 **OA available**.

[25] Samuel Gratzl, Nils Gehlenborg, Alexander Lex, Hanspeter Pfister, and Marc Streit. 2014. Domino: Extracting, comparing, and manipulating subsets across multiple tabular datasets. *IEEE transactions on visualization and computer graphics* 20, 12 (2014), 2023–2032.

[26] Jens Grubert, Eyal Ofek, Michel Pahud, and Per Ola Kristensson. 2020. Back to the Future: Revisiting Mouse and Keyboard Interaction for HMD-based Immersive Analytics. arXiv:2009.02927 [cs.HC]

[27] Jeffrey Heer and Ben Shneiderman. 2012. Interactive Dynamics for Visual Analysis: A Taxonomy of Tools That Support the Fluent and Flexible Use of Visualizations. *Queue* 10, 2 (Feb. 2012), 30–55. https://doi.org/10.1145/2133416.2146416

[28] Ken Hinckley, Randy Pausch, John C Goble, and Neal F Kassell. 1994. Passive Real-World Interface Props for Neurosurgical Visualization. In *Proc. CHI*. ACM, New York, 452–458. https://doi.org/10.1145/191666.191821 **OA available**.

[29] Sebastian Hubenschmid, Johannes Zagermann, Simon Butscher, and Harald Reiterer. 2021. *STREAM: Exploring the Combination of Spatially-Aware Tablets with Augmented Reality Head-Mounted Displays for Immersive Analytics.* Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3411764.3445298

[30] Samuel Huron, Sheelagh Carpendale, Alice Thudt, Anthony Tang, and Michael Mauerer. 2014. Constructive Visualization. In *ACM conference on Designing Interactive Systems in 2014 (DIS '14 Proceedings of the 2014 conference on Designing interactive systems)*. ACM, ACM, Vancouver, Canada, Pages 433–442. https://doi.org/10.1145/2598510.2598566 Best Paper Honorable Mention.

[31] Samuel Huron, Yvonne Jansen, and Sheelagh Carpendale. 2014. Constructing Visual Representations: Investigating the Use of Tangible Tokens. *IEEE Transactions on Visualization and Computer Graphics* 20, 12 (Aug. 2014), 1. https://doi.org/10.1109/TVCG.2014.2346292 **OA available**.

[32] Petra Isenberg, Danyel Fisher, Sharoda A. Paul, Meredith Ringel Morris, Kori Inkpen, and Mary Czerwinski. 2012. Co-located Collaborative Visual Analytics Around a Tabletop Display. *IEEE Transactions on Visualization and Computer*

Graphics 18, 5 (2012), 689–702. https://doi.org/10.1109/TVCG.2011.287 Appeared in pre-print 12/2011.

[33] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible Bits: Towards Seamless Interfaces Between People, Bits and Atoms. In *Proc. CHI*. ACM, New York, 234–241. https://doi.org/10.1145/258549.258715 **OA available**.

[34] Paul Issartel, Florimond Guéniat, and Meryem Ammi. 2014. Slicing Techniques for Handheld Augmented Reality. In *Proc. 3DUI*. IEEE Computer Society, Los Alamitos, 39–42. https://doi.org/10.1109/3DUI.2014.6798839 **OA available**.

[35] Brian Jackson, Tung Yuen Lau, Damien Schroeder, Kimani C Toussaint, and Daniel F Keefe. 2013. A Lightweight Tangible 3D Interface for Interactive Visualization of Thin Fiber Structures. *IEEE Transactions on Visualization and Computer Graphics* 19, 12 (Dec. 2013), 2802–2809. https://doi.org/10.1109/TVCG.2013.121 **OA available**.

[36] Yvonne Jansen, Pierre Dragicevic, and Jean-Daniel Fekete. 2013. Evaluating the Efficiency of Physical Visualizations. In *Proceedings of the 2013 Annual Conference on Human Factors in Computing Systems (CHI 2013)*. ACM, ACM, Paris, France, 2593–2602. https://doi.org/10.1145/2470654.2481359 **OA available**.

[37] Waqas Javed and Niklas Elmqvist. 2012. Exploring the design space of composite visualization. In *2012 ieee pacific visualization symposium*. IEEE, 1–8.

[38] Rajiv Khadka, James Money, and Amy Banić. 2018. Body-Prop Interaction: Augmented Open Discs and Egocentric Body-Based Interaction for Exploring Immersive Visualizations. In *Proc. ISS* (Tokyo, Japan). ACM, New York, 327–332. https://doi.org/10.1145/3279778.3281458 **OA available**.

[39] P. Koytek, C. Perin, J. Vermeulen, E. André, and S. Carpendale. 2018. MyBrush: Brushing and Linking with Personal Agency. *IEEE Transactions on Visualization and Computer Graphics* 24, 1 (2018), 605–615. https://doi.org/10.1109/TVCG.2017.2743859 **OA available**.

[40] Mathieu Le Goc, Lawrence H Kim, Ali Parsaei, Jean-Daniel Fekete, Pierre Dragicevic, and Sean Follmer. 2016. Zooids: Building Blocks for Swarm User Interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST)*. Tokyo, Japan. https://doi.org/10.1145/2984511.2984547 **OA available**.

[41] Mathieu Le Goc, Charles Perin, Sean Follmer, Jean-Daniel Fekete, and Pierre Dragicevic. 2019. Dynamic Composite Data Physicalization Using Wheeled Micro-Robots. *IEEE Transactions on Visualization and Computer Graphics* 25, 1 (Jan. 2019), 737–747. https://doi.org/10.1109/TVCG.2018.2865159 **OA available**.

[42] Mathieu Le Goc, Charles Perin, Sean Follmer, Jean-Daniel Fekete, and Pierre Dragicevic. 2019. Dynamic Composite Data Physicalization Using Wheeled Micro-Robots. *IEEE Transactions on Visualization and Computer Graphics* 25, 1 (Jan. 2019), 737–747. https://doi.org/10.1109/TVCG.2018.2865159

[43] Benjamin Lee, Xiaoyun Hu, Maxime Cordeil, Arnaud Prouzeau, Bernhard Jenny, and Tim Dwyer. 2021. Shared Surfaces and Spaces: Collaborative Data Visualisation in a Co-located Immersive Environment. *IEEE Transactions on Visualization and Computer Graphics* 27, 2 (2021), 1171–1181. https://doi.org/10.1109/TVCG.2020.3030450 **OA available**.

[44] Daniel Leithinger, Sean Follmer, Alex Olwal, Samuel Luescher, Akimitsu Hogge, Jinha Lee, and Hiroshi Ishii. 2013. Sublimate: State-Changing Virtual and Physical Rendering to Augment Interaction with Shape Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Paris, France) *(CHI '13)*. Association for Computing Machinery, New York, NY, USA, 1441–1450. https://doi.org/10.1145/2470654.2466191 **OA available**.

[45] Daniel Leithinger and Hiroshi Ishii. 2010. Relief: A Scalable Actuated Shape Display. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction* (Cambridge, Massachusetts, USA) *(TEI '10)*. Association for Computing Machinery, New York, NY, USA, 221–222. https://doi.org/10.1145/1709886.1709928 **OA available**.

[46] Catherine Letondal, Christophe Hurter, Rémi Lesbordes, Jean-Luc Vinot, and Stéphane Conversy. 2013. Flights in my hands: coherence concerns in designing Strip'TIC, a tangible space for air traffic controllers. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2175–2184.

[47] Lars Lischke, Paweł W. Woundefinedniak, Sven Mayer, Andreas Preikschat, and Morten Fjeld. 2017. Using Variable Movement Resistance Sliders for Remote Discrete Input. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces* (Brighton, United Kingdom) *(ISS '17)*. Association for Computing Machinery, New York, NY, USA, 116–125. https://doi.org/10.1145/3132272.3134135

[48] David López, Lora Oehlberg, Candemir Doger, and Tobias Isenberg. 2016. Towards an Understanding of Mobile Touch Navigation in a Stereoscopic Viewing Environment for 3D Data Exploration. *IEEE Transactions on Visualization and Computer Graphics* 22, 5 (May 2016), 1616–1629. https://doi.org/10.1109/TVCG.2015.2440233 **OA available**.

[49] Karljohan Lundin (Palmerius), Matthew Cooper, Anders Persson, Daniel Evestedt, and Anders Ynnerman. 2007. Enabling design and interactive selection of haptic modes. *Virtual Reality* (2007). https://doi.org/10.1007/s10055-006-0033-7 **OA available**.

[50] Karljohan Lundin (Palmerius), Mattias Sillé;n, Matthew Cooper, and Anders Ynnerman. 2005. Haptic Visualization of Computational Fluid Dynamics Data Using Reactive Forces. In *International Conference on Visualization and Data Analysis, San Jose, USA*. 95–102. https://doi.org/10.1117/12.587029 **OA available**.

[51] Kim Marriott, Falk Schreiber, Tim Dwyer, Karsten Klein, Nathalie Henry Riche, Takayuki Itoh, Wolfgang Stuerzlinger, and Bruce H Thomas. 2018. *Immersive Analytics*. Vol. 11190. Springer, Berlin, Heidelber, Germany. https://doi.org/10.1007/978-3-030-01388-2

[52] Paul Marshall, Rowanne Fleck, Amanda Harris, Jochen Rick, Eva Hornecker, Yvonne Rogers, Nicola Yuill, and Nick Sheep Dalton. 2009. Fighting for control: Children's embodied interactions when using physical and digital representations. In *Proc. CHI*. ACM, New York, 2149–2152. https://doi.org/10.1145/1518701.1519027 **OA available**.

[53] Izabel C. Olson, Zeina Atrash Leong, Uri Wilensky, and Mike S. Horn. 2011. "It's just a toolbar!" Using tangibles to help children manage conflict around a multi-touch tabletop. In *Proc. TEI*. ACM, New York, 29–36. https://doi.org/10.1145/1935701.1935709 **OA available**.

[54] Ivan Poupyrev, Tatsushi Nashida, Shigeaki Maruyama, Jun Rekimoto, and Yasufumi Yamaji. 2004. Lumen: Interactive Visual and Shape Display for Calm Computing. In *ACM SIGGRAPH 2004 Emerging Technologies* (Los Angeles, California) *(SIGGRAPH '04)*. Association for Computing Machinery, New York, NY, USA, 17. https://doi.org/10.1145/1186155.1186173

[55] Anne Roudaut, Abhijit Karnik, Markus Löchtefeld, and Sriram Subramanian. 2013. Morphees: Toward High "Shape Resolution" in Self-Actuated Flexible Mobile Devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Paris, France) *(CHI '13)*. Association for Computing Machinery, New York, NY, USA, 593–602. https://doi.org/10.1145/2470654.2470738 **OA available**.

[56] Cheryl Savery, Christophe Hurter, Rémi Lesbordes, Maxime Cordeil, and T. C. Nicholas Graham. 2013. When Paper Meets Multi-touch: A Study of Multi-modal Interactions in Air Traffic Control. In *Human-Computer Interaction – INTERACT 2013*. Springer Berlin Heidelberg, 196–213. https://doi.org/10.1007/978-3-642-40477-1_12

[57] Steven Schkolne, Hiroshi Ishii, and Peter Schroder. 2004. Immersive design of DNA molecules with a tangible interface. In *Proc. Visualization*. IEEE Computer Society, Los Alamitos, 227–234. https://doi.org/10.1109/VISUAL.2004.47 **OA available**.

[58] Bertrand Schneider, Kshitij Sharma, Sébastien Cuendet, Guillaume Zufferey, Pierre Dillenbourg, and Roy D Pea. 2015. 3D tangibles facilitate joint visual attention in dyads. International Society of the Learning Sciences, Inc.[ISLS].

[59] Mickael Sereno, Xiyao Wang, Lonni Besançon, Michael J Mcguffin, and Tobias Isenberg. 2021. Collaborative Work in Augmented Reality: A Survey. *IEEE Transactions on Visualization and Computer Graphics* (2021). https://doi.org/10.1109/TVCG.2020.3032761 **OA available**.

[60] Peng Song, Wooi Boon Goh, Chi-Wing Fu, Qiang Meng, and Pheng-Ann Heng. 2011. WYSIWYF: Exploring and Annotating Volume Data with a Tangible Handheld Device. In *Proc. CHI*. ACM, New York, 1333–1342. https://doi.org/10.1145/1978942.1979140 **OA available**.

[61] Martin Spindler, Sophie Stellmach, and Raimund Dachselt. 2009. PaperLens: Advanced Magic Lens Interaction Above the Tabletop. In *Proc. ITS* (Banff, Alberta, Canada). ACM, New York, 69–76. https://doi.org/10.1145/1731903.1731920 **OA available**.

[62] Martin Spindler, Christian Tominski, Heidrun Schumann, and Raimund Dachselt. 2010. Tangible Views for Information Visualization. In *ACM International Conference on Interactive Tabletops and Surfaces* (Saarbrücken, Germany) *(ITS '10)*. Association for Computing Machinery, New York, 157–166. https://doi.org/10.1145/1936652.1936684

[63] Paul Strohmeier and Kasper Hornbæk. 2017. Generating Haptic Textures with a Vibrotactile Actuator. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 4994–5005. https://doi.org/10.1145/3025453.3025812

[64] Faisal Taher, John Hardy, Abhijit Karnik, Christian Weichel, Yvonne Jansen, Kasper Hornbæk, and Jason Alexander. 2015. Exploring Interactions with Physically Dynamic Bar Charts. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 3237–3246. https://doi.org/10.1145/2702123.2702604

[65] Brygg Ullmer, Hiroshi Ishii, and Robert JK Jacob. 2003. Tangible Query Interfaces: Physically Constrained Tokens for Manipulating Database Queries.. In *INTERACT*, Vol. 3. 279–286. **OA available**.

[66] Sebastian Ullrich and Tornsten Kuhlen. 2012. Haptic Palpation for Medical Simulation in Virtual Environments. *IEEE Transactions on Visualization and Computer Graphics* 18, 4 (April 2012), 617–625. https://doi.org/10.1109/TVCG.2012.46

[67] T. van Reimersdahl, F. Bley, T. Kuhlen, and C. H. Bischof. 2003. Haptic Rendering Techniques for the Interactive Exploration of CFD Datasets in Virtual Environments. In *Proc. Workshop on Virtual Environments* (Zurich, Switzerland). ACM, New York, 241–246. https://doi.org/10.1145/769953.769981 **OA available**.

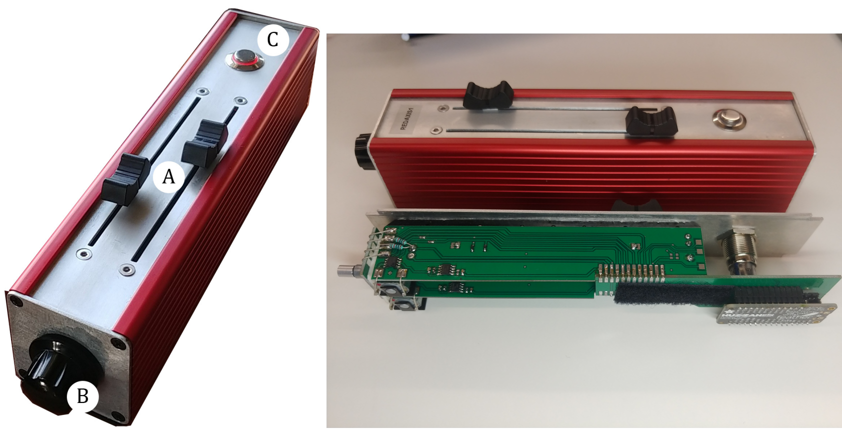
[68] Christophe Viau and Michael J McGuffin. 2012. ConnectedCharts: explicit visualization of relationships between data graphics. In *Computer Graphics Forum*, Vol. 31. Wiley Online Library, 1285–1294.

[69] Xiyao Wang, David Rousseau, Lonni Besançon, Mickael Sereno, Mehdi Ammi, and Tobias Isenberg. 2020. Towards an Understanding of Augmented Reality Extensions for Existing 3D Data Analysis Tools. In *CHI '20 - 38th SIGCHI conference on Human Factors in computing systems*. Honolulu, United States. https://doi.org/10.1145/3313831.3376657 **OA available**.

[70] Lesley Xie, Alissa N. Antle, and Nima Motamedi. 2008. Are tangibles more fun? Comparing children's enjoyment and engagement using physical, graphical and tangible user interfaces. In *Proc. TEI*. ACM, New York, 191–198. https://doi.org/10.1145/1347390.1347433 **OA available**.

9 APPENDIX

Additional figures:



(a) Two actuated sliders (A); Rotary push encoder (B); Push button (C)

(b) Internal circuit board assembly

Fig. 9. MADE-Axis key components.

Received July 2021; revised September 2021; accepted September 2021

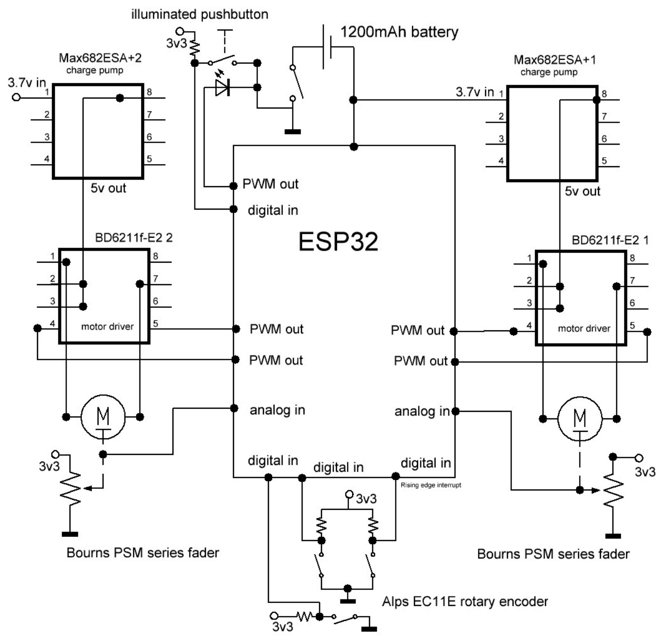


Fig. 10. Schematic diagram.