OCTOPUS: A MULTICHANNEL WEARABLE VIBROTACTILE HAPTIC FEEDBACK INTERFACE FOR EMBODIED EXPLORATION IN INTERACTIVE DATA DISPLAY SYSTEMS

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ABSTRACT

In this demo we present Octopus, a wearable interface designed to explore how multimodal haptic technology can support navigation of complex interactive data displays. Octopus combines multichannel vibrotactile feedback with gestural navigation control using gyroscope and accelerometer inputs. It serves as an open-ended, customizable controller and data display interface enabling embodied data navigation, interaction, and understanding. Octopus is integrated with Dark Sonification, an interactive system for data perceptualization through affect combining audiovisual display modalities. Octopus functions both as a navigation controller for gestural interaction and as a data display through spatially distributed vibrotactile feedback across the forearm and upper arm. We are especially interested in investigating whether a wearable, multichannel haptic interface like Octopus provides more nuanced bodily awareness of data structures compared to conventional handheld controllers. The demo presents two interaction modes, inviting the community to experience and reflect on these strategies for embodied data perceptualization.

1. INTRODUCTION

Exploratory data analysis (EDA) is a common method for conducting scientific research with data collections, mainly relying on visualisation as a means of display [18]. Nevertheless, scientific groups often include individuals who are blind or have low vision, raising questions of accessibility in a method highly relying on visualisation. Sonification has been proposed as an option to address this challenge [14], however, a perceptually meaningful display in visualisation might not have a straight correlation with a sonification design, as both modalities deal with different sensory capacities and different ways of structuring perception affecting meaning-making processes [2]. Additionally, as scientists increasingly emphasise the dissemination of their research (often driven by funding requirements), scientific data displays often lack the appeal to engage non-specialized audiences.

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In response to these challenges, the data display research community has increasingly focused on multimodal display systems that integrate various modalities, with strong emphasis on the combination of visual and sound [2, 4]. Multimodal displays aim to provide an improved perceptualization experience for data exploration [4] and a toolkit of assistive technologies for researchers with diminished sensory capacities [20]. Nevertheless, questions of perceptually meaningful mapping persist in multimodal contexts. Caiola et al. [2] conducted a thorough study of 80 audiovisual sonification projects to understand feature mapping correspondence between audio and visual modalities, analysing how visual and sound parameters aligned across different design examples. However, multimodal interaction research generally does not address the dimension of bodily engagement across modalities, nor does it explore how the integrated modalities correlate with bodily affectation and the spatiotemporal aspects of the data being represented.

In this demo we present a wearable interface called Octopus. With this project we aim to explore how a multimodal haptic interface can help navigating complex interactive data displays. Octopus implements multichannel vibrotactile feedback in combination with gestural navigation control via gyroscope and accelerometer. Octopus is designed as an open-ended and customizable controller and data display interface designed to enable embodied data navigation, interaction, and understanding. The design of Octopus is extending the rationale of wearable interfaces for gestural musical expression [16] by incorporating the functionality of data display in the navigation controller via six independent vibrotactile feedback channels.

For this purpose, Octopus is integrated with an existing multimodal data display system called Dark Sonification, which is an interactive system for data perceptualization through affect that integrates audiovisual display implemented in Python and vibrotactile feedback via PS5 Dual Sense gaming controllers (Fig. 1) [3]. This approach is based on the techniques of data physicalization, by incorporating different sensory modalities in the data exploration process. Octopus functions as both a navigation controller, enabling gestural interaction, and as a data display device through spatially distributed vibrotactile haptic feedback across the forearm and the upper arm (Fig. 2). This dual function design aims to replace the PS5's limited interaction capabilities of joystick and dual motor haptic feedback with richer embodied interaction pos-

Figure 1: PlayStation 5 Dual Sense controller used for interactive navigation with the Dark Sonification framework.

Figure 2: The Octopus wearable interface.

sibilities. We are especially interested in investigating if a wearable, multichannel haptic interface like Octopus provides more nuanced bodily awareness of data structures compared to conventional handheld controllers.

This demo presents two modes of interaction strategies with an interactive data display system designed to explore this question, inviting the community to experience and reflect on these strategies of data perceptualization.

2. CONTEXT

Vibrotactile haptic feedback is deeply integrated into everyday technology such as mobile phones, tablets, smartwatches, gaming controllers, and AR/VR interfaces [12]. Furthermore, haptic feedback has been investigated in the context of assistive technologies for spatial navigation and information access for individuals with low vision as in the Sound of Vision project [10], as well as in data physicalization and visualisation [1]. Yeganeh et al. [19] further discuss haptic spatial resolution linked to actuator positioning on the body rather than through frequency modulation. This spatial distribution conceptualization is core to our approach with Octopus which utilises multiple vibrotactile actuators across the forearm and the upper arm to create mapping strategies between actuator position and system parameters.

Multimodal interaction has become central in contemporary Human-Computer Interaction research and Human-Machine Interface design with studies showing that combining different sensory modalities can enhance performance and engagement with interfaces [8]. Multimodal stimuli can lead to the superadditive effect of multisensory integration, where the response to combined sensory inputs is stronger than the sum of responses to individual inputs [11]. This effect suggests that haptic feedback, when combined with audio and visual display, may facilitate richer perceptual experiences in data exploration contexts. Nevertheless, critical questions remain regarding the design of multimodal interfaces for exploratory data analysis and how to map data features to haptic parameters, including which types of data are better for haptic encoding, the limit of haptic mapping based on data resolution, and how such interfaces shared among a group of researchers with varied sensory capacities might promote collective meaning-making aligned with Magnusson's [13] idea of interfaces as boundary objects.

Research in multimodal data exploration has produced diverse approaches to integrating haptic feedback with visual and auditory displays. PolySurface combines visual projection with pneumatic shape-changing surfaces, allowing users to physically manipulate data representations through deformable interfaces [5]. Robographics combine audio and tactile interaction through dynamic graphic displays for data exploration [9]. Similarly, SlideTone and Tilt-Tone communicate data trends via haptics based on graph shape characteristics [6]. Furthermore, inFORM uses arrays of motorized pins to render three-dimensional data representations to explore through direct touch [7]. Beyond data exploration contexts, work on somaesthetic design by Schiphorst [15] has demonstrated how wearable haptic interfaces can support bodily attunement and first-person embodied experience in interaction design. Extensive research on numerous aspects of the somatic experience and bodily awareness through multimodal sensory feedback has also been conducted by the i_mBody lab in relation to various scientific and artistic research questions with projects such as Movits [17].

While these haptic integrations demonstrate significant contribution to the field, the exchange of knowledge acquired from research on wearable technologies' development with research conducted in the field of multimodal data displays has been sparsely investigated. Moreover, while the aforementioned technologies apply data physicalization by designing artifacts that are positioned as extensions to the body, Octopus' integration with Dark Sonification data display design system suggests an embodied interaction where the controller becomes part of the body in the form of a wearable interface. This approach can lead to insights for the creation of an inclusive space for data exploration for individuals with varied sensory capacities.

3. DESIGN AND TECHNICAL REALISATION

3.1. The Octopus Interface

Octopus is a wearable interface in the form of a sleeve made of elastic fabric providing input and output data for interfacing physically with data displays in Python programming language. The core of the system consists of a communication node built around an ESP32 microcontroller (Fig. 3) which can receive and send data to a computer through the ESP-Now wireless protocol. Seven peripherals can be attached to the communication node, one of which

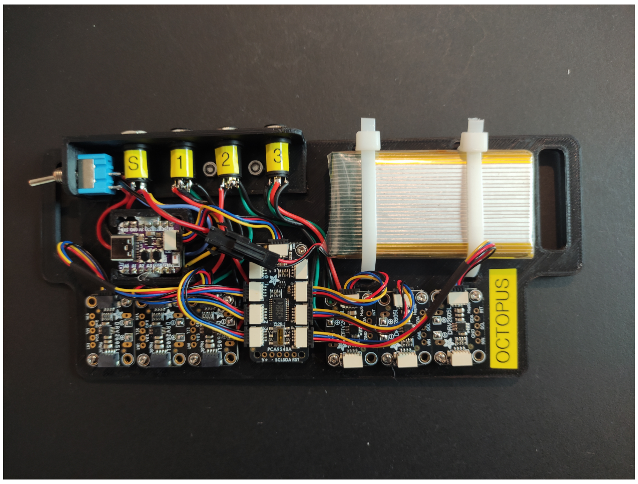

Figure 3: The communication node for the Octopus wearable.

acts as an input and six as output. As input we use an Inertial Measurement Unit (IMU) which provides 3D orientation via gyroscope and motion acceleration measurements via accelerometer enabling gestural spatial navigation by tilting the wrist. The outputs provide vibrotactile feedback via six fixed frequency linear resonant actuators (LRA) that can be configured and driven independently. The configuration of the haptic feedback has three variables: vibrator index, intensity, and duration.

3.2. The Dark Sonification Framework

The Dark Sonification framework, developed by PhD researcher Miguel Angel Crozzoli at the Intelligent Instruments Lab, is a multimodal exploratory data analysis design framework for big data [3]. More specifically, Dark Sonification investigates the emergence of knowledge through affect by interacting with data transformed with machine learning algorithms (such as K-means, UMAP etc) through visuals, space, sound, and vibrations as different modalities of representation of changes in data. The results of data transformations in Dark Sonification get displayed in 2D graphic planes (Fig. 4) that can be further explored across the aforementioned modalities simultaneously via navigation by the user. Data navigation in Dark Sonification is implemented with the use of a hand-held PS5 gaming console controller which is geared with vibrotactile feedback actuators. During navigation, vibrotactile feedback is employed to indicate data points of specific interest, e.g. anomalies detected by Isolation Forest algorithm.

3.3. Integration of the Octopus Interface with Dark Sonification

Octopus' integration with Dark Sonification investigates an alternative to the use of the PS5 controller both as a navigation interface for the data display and as a data display through haptic feedback. Octopus' gestural navigation capabilities replace the joystick input of the PS5 controller as a navigation system in Dark Sonification. Furthermore, with Octopus' integration we aim to enhance the haptic feedback of the interaction by increasing the haptic feedback channels from two to six. The data display designed for the demonstration is utilising a multidimensional toy dataset produced

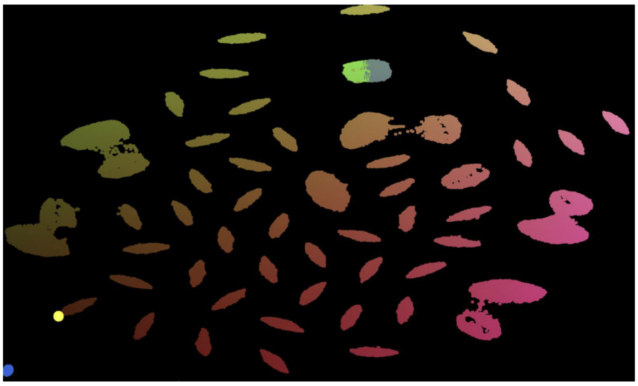

Figure 4: Visual display of Dark Sonification.

in a controlled environment. The framework of Dark Sonification includes a synthetic data generator with capacity to control the amount of the produced data points, the amount of features for each data point, cluster id for each data point based on density and distance, and anomalies within clusters.

3.4. Modes of Interaction

To test the navigation control and haptic feedback display of Octopus we have designed two modes of interaction with Dark Sonification. The first mode focuses on spatial boundary detection and uses the four distributed haptic channels across the forearm. As the user moves through the data space via gestural control, different actuators activate based on their position relative to boundaries of the 2D data space creating a spatially-grounded sense of "where" they are within the dataset. The second mode is focused on categorical data awareness by activating the two actuators placed to the upper arm when data values cross specific thresholds. In this mode the threshold defines anomalies in the dataset.

4. SPECULATION AND FUTURE STEPS

Through our experience integrating Octopus with Dark Sonification we observed that the shift from a handheld controller to a wearable distributed haptic interface significantly changes the embodied experience of data exploration. Unlike handheld interfaces that require grip tension and thumb-based navigation, the wearable configuration frees the hands while distributing feedback across the forearm, enabling a more natural and deeper attunement to felt sense. Through this integration, we want to form a basis for speculation around the question of how wearables with spatially distributed haptic feedback can enhance embodied data exploration in multimodal display systems.

Furthermore, several design considerations emerged regarding multimodal mapping strategies. These include questions about how haptic skin resolution constrains the granularity of displayable data details, how to effectively encode continuous versus discrete data parameters through vibrotactile feedback, and which data features benefit most from haptic encoding compared to visual or auditory display. Our preliminary observations raise questions about whether spatially distributed haptic feedback might enable the design of efficient assistive interfaces for interactive data display systems for researchers with diminished sensory capacities. Moreover, Octopus is designed to support multiple wearable devices interacting with the same dataset providing for collaborative data exploration. This would facilitate collective meaning-making for groups of researchers with diverse sensory capacities on fields of inquiry that require empirical investigation through collaborative data exploration studies.

Further research, prototyping, testing and evaluation within protocol standards is required to produce solid answers to these questions.

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