BRIX5: Prototyping Modules for Wearables with Vibrotactile Haptics

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Abstract. Few open and reproducible tools exist for prototyping wearable sensor-actor systems with state-of-the art vibrotactile haptics, e.g., for augmented feedback applications or novel human-computer interfaces. In this paper, we present BRIX5, a modular platform for prototyping feature-rich wearables. Based on the interconnect specifications Qwiic and Feather, BRIX5 is compatible with a rapidly growing open ecosystem. Our contribution are an adaptable base module and compact extensions for motion sensors, arrays of both narrow-, and wide-band voice coil tactile actuators. Filling the gap between proprietary, off-the-shelf wearables and custom prototypes, we release BRIX5 as open hardware, as a step towards a common platform for shared vibrotactile wearable research and teaching.

Keywords: Vibrotactile · Wearables · Prototyping · Physical Computing · Open Hardware

1 Introduction

A major barrier to entry in wearables creation is the lack of common rapid prototyping tools. Previously proposed toolkits, such as YAWN [11] and BRIX$_2$ [15], have remained isolated solutions not easily reproduced at scale nor interoperable with a growing variety of breakout boards. These on their own require substantial integration engineering to be suitable for use in wearables. For wearable vibrotactile (VT) haptics and the study of rich, anatomy-adapted stimuli to eventually leverage the distributed nature of the sense of touch, even fewer options exist. As control of tactors arrays and embedded synthesis for wide-band tactors remains difficult, most research to date still relies on eccentric rotating mass motors (ERMs) as tactors (tactile actuators).

In this paper, we present the BRIX5 toolkit for the development of such multi-channel VT wearables and the iterative design process from technology probes to functional prototypes. Instead of creating an isolated toolkit, BRIX5 is an open concept focussing on compatiblity and an intentionally minimal modular design. Based on the Feather and Qwiic specifications (Sec. 2.2), it is compatible with over 200 existing extensions.

Here, we present an adaptable base controller, providing functionality of common watch form-factor wearables to bootstrap the wearable development process (Sec. 3.1). To be used in combination with the base module or other systems, we provide extensions for compact motion sensors as well as means for control of arrays of narrow-, and wide-band tactors (Sec. 3.2-3.4).

BRIX5 is open hardware, as a step towards a reproducible collaborative platform for shared vibrotactile wearable research and teaching. We are inspired by similar approaches for grounded haptics (e.g., Haply [4]) and stationary, multi-channel VT control (Syntacts [8]).

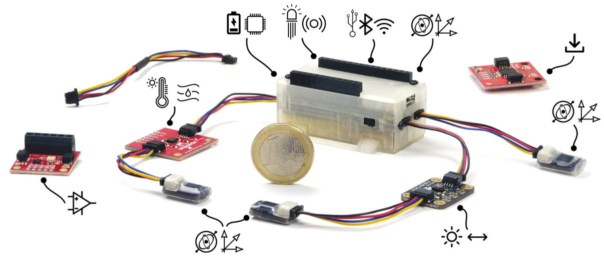

Fig. 1. BRIX5 base controller with example Qwiic extensions (Pictograms from the Noun Project)

2 Background and Motivation

2.1 Vibrotactile Haptics

In this paper, we focus on supporting the most common types of VT actuators: Narrow-band tactors(NBT), such as ERMs and linear resonant actuators (LRAs), and wide-band voice coil tactors (WBT).

In ERMs, a higher rotation speed of the motor translates to both a higher amplitude and vibration frequency; ERM control can be as simple as on-off signals. In LRAs, a coil excites a spring-suspended magnet, allowing control of amplitude independent of the fixed resonance frequency. More durable and energy conserving, LRAs are gradually replacing ERMs in mobile devices [3]. A single, purpose-built driver chip is usually used per tactor to generate a full-swing square wave.

Voice coil WBTs are related to LRAs in construction but much more uniform in frequency response.[1] Voice coil tactors are driven like loudspeakers with an audio signal and amplifier. Examples include the Haptuator tactors [13], designed for a linear response across the haptic bandwidth, and the Lofelt L5 tactor, optimized for continuous use and frequencies below 100 Hz, deemed more comfortable for prolongued stimuli [3].

Currently, both narrow- and wide-band tactors have their place [3]; NBTs are usually more compact and affordable while WBTs allow more complex waveforms to be rendered. WBTs potential remains unleveraged in a broader wearable context, this is partly due to requisite haptic signal synthesis remaining a nascent area of research. Signal synthesis can be realized with general-purpose sound synthesis software such as SuperCollider or Pure/Purr Data. For embedded systems, two options are the Mozzi Arduino library and the Audio library for the Teensy range of microcontrollers. Open tools dedicated to designing VT stimuli are slowly emerging, such as Macaron [9] and Syntacts [8].

[1] The recent "HD Haptics" specification requires expression of at least three perceptually distinct frequencies (`https://github.com/HapticsIF/HDActuatorSpec`).

2.2 Physical Computing and Wearable Prototyping

The open hard-/software ecosystem that emerged around platforms such as Arduino and Raspberry Pi provides unprecedented access to microcontrollers and periphery, and is connecting diverse maker communities. One common way for microcontroller and extension breakout boards to connect is through 0.1"-pitch pin-headers, either stacking on top each other, or through wire/breadboard for temporary connection. Besides the original Arduino (Uno) and Raspberry Pi footprints for such stackable boards, the Adafruit Feather specification[2] is becoming popular. It defines a common footprint (0.9"×2"), function (USB interface, power supply/charging circuit), and two rows of 0.1" headers for extension "Wings". At the time of writing, over 50 different boards combining various microcontrollers and wireless interfaces (e.g., Bluetooth, WiFi, LoRaWAN, XBee, and cellular networks) and over 80 wings were available from Adafruit/SparkFun alone.

For longer distances, and daisy-chaining extensions, a wire-based interconnect can be more suitable, the I^2C serial interface being the commonest digital interface. Wearables require robust connection and thus benefit from a standardized, cable-based interconnect for I^2C, such as the the earlier, proprietary Seeedstudio Grove and the more recent, open, and more compact Qwiic system.[3] The Qwiic system allows microcontrollers ranging from lowest-power (Atmel ATMega, Nordic nRF52) to single-board computers (Raspberry Pi) to share extensions, and has rapidly gained acceptance across the open ecosystem.

Few modular toolkits specifically for wearable haptics prototyping have been proposed from the academic side, though control of single ERMs is often possible. Designed for sensorimotor rehabilitation applications, Xu et al. present a wireless system of distributed nodes for motion sensing and ERM haptics [12]. Thar et al. describe the YAWN system [11], a custom bus-based system interconnecting through conductive fabric band and a number of extension modules, including sensors and ERM tactors. Zehe developed the $BRIX_2$ [15] system, a compact toolkit for wearable prototyping and teaching physical computing housed in interlocking bricks. A base module with motion sensor and wireless interface can hold three extensions, such as various sensors, a quad-channel ERM driver, and an audio/haptic synthesis/driver extension based on the Mozzi library. Zook and others' Snaptics provide an open source-based toolkit for various types of wearable haptics, including vibrotactile, primarily contributing a snapping mounting system [16]. Pezent and others' Syntacts provides a reproducible amplifier board for eight WBTs for stationary setups [8].

3 BRIX5 Implementation

To our knowledge, no existing wearable prototyping toolkits are modular and provide means for controlling arrays of NBTs/WBTs. The open hardware ecosystem's recent embrace of Qwiic and Feather is a game-changer for embedded rapid

[2] https://learn.adafruit.com/adafruit-feather/feather-specification

[3] https://sparkfun.com/qwiic, aka. Adafruit Stemma QT, Smart Prototyping ZIO

prototyping. We based BRIX5 on these two specifications to support a wide range of existing microcontrollers, extensions, and associated software. Building on established, well-documented and supported platforms lowers the bar to entry and allows for knowledge generalization. Modularity allows adaptation to use cases and users, and can support an iterative development approach through (re-)use and extension as prototypes and available technology evolve. Iteration and adaptability are key in rapidly determining sensor/actuator choice and placement location of on the body [14]. Compatibility and minimal custom electronics reduce development efforts and increases repairability, especially important in wearable development, where prototypes are subject to significant wear-and-tear [3]. A toolkit such as BRIX5 can at best remain a work-in-progress, a flexible mediator between established and emerging technologies. Our design prioritizes an increase in flexibility and reduced maintenance over the highest-possible integration, minimizing lock-in to specific technologies, such as microcontrollers or wireless standards.

In the following, we present an adaptable wearable base controller (Sec. 3.1), extensions for motion sensors (Sec. 3.2), and for control of multi-channel narrow- and wide-band VT haptics (Sec. 3.3 and Sec. 3.4). We conclude with integration aspects, such as power supply, housing, and reproducibility (Sec. 3.5).

3.1 BRIX5 Base Controller

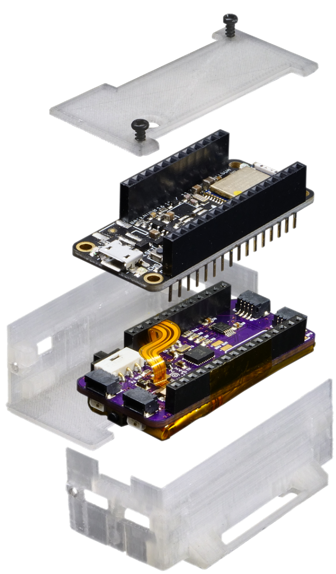

Fig. 2. Exploded view

The base controller solves the problem of **bootstrapping**, extending Feather microcontroller breakout board (Sec. 2.2) with common essentials needed to turn it into an extensible wearable unit. The feather stacks on a custom printed circuit board (PCB) (Fig. 2) that integrates a 9-axis **motion sensor** (BNO0XX, see Sec. 3.2), an LRA **tactor** and driver (Long LVM061530B; TI DRV2605, see Sec. 3.3), and a **Real-Time Clock** (RTC, Micro Crystal RV1805) for timestamping sensor data or synchronization between multiple units [3]. User input can be captured with a **push-button**, and two adressable **RGB LEDs** allow simple displays. The PCB also provides a **power switch** for the lithium polymer **battery** (450 mAh) fitted to the bottom of the base PCB. We tested nRF52 and ESP32 feathers, and others should work similarly.

The base module can be extended via a top-mounted Feather wing and through four **Qwiic headers** on the side, for which a **bus power reset circuit** allows automated recovery from hangups. Qwiic cables up to 500 mm are readily and cheaply available and can easily be extended with coiled or shielded wire if robustness or length is required, I^{2}C-over-RJ485 and signal-reconditioning modules exist to cover very long distances.

3.2 Motion / Orientation Sensor: Mini/MicroBNO Extensions

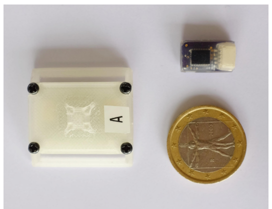

Fig. 3. BNOs

Our miniaturized BNO extensions solve the problem of **compact, low-drift motion/ orientation sensors**, commonly required in wearable projects. The chosen Bosch BNO055, a 9-axis magnetic, angular rate, and gravity sensor, provides raw and filtered data as well as best-in-class sensor-fusion for absolute orientation estimation [5]. While the base module includes one BNO sensor, we designed miniaturized extensions in two sizes, miniBNO and microBNO for applications requiring additional sensors (Fig. 3). The mini-size is suitable for strap-mounting and exposes more chip configuration options. The micro-size is approximately fingernail-sized and meant to be integrated into garments, e.g., glove fingertips, or affixed to the body directly with adhesive tape. For new setups – though our PCB designs accommodates all variants – we use more recent CEVA BNO080/085 variants. These provide orientation output rates up to 400 Hz, allow flexible configuration of input sensors, and exhibit less drift. Through I^{2}C-multiplexers, we have used up to 16 BNOs simultaneously.

3.3 Multichannel LRA and ERM: QuadDRV

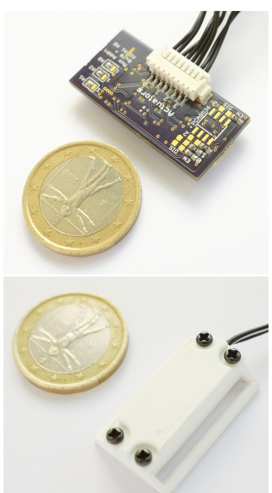

Fig. 4. QuadDRV, LRA Tactor

Our QuadDRV extension enables **closed-loop control of NBT arrays**. To date, most VT wearables to date drive ERMs in an open-loop fashion, which results in slow ramp-up and ramp-down of vibration intensity. The QuadDRV module (Fig. 4) drives four ERMs or LRAs, and is built around four TI DRV2605L haptic drivers multiplexed by a I^{2}C bus switch. For ERMs, the DRV2605L allows active braking and overdrive, improving ERM pulse sharpness significantly to a level comparable to that of voice coils [2]. For LRAs, it provides automatic resonance tuning, necessary to derive optimal output amplitude despite resonance frequency varying between tactor samples and with integration. The DRV2605L has a built-in effect library and sequencer and can also operate in streaming mode for external control. Tactors are connected through a 8-pin Molex Picoblade (1.25 mm pitch) plug, chosen for its compact size and the availability of manufacturer-direct pre-made cables.

3.4 Wide-band Tactors: Audio-400, Lofelt L5 and Amp-200, Adapters

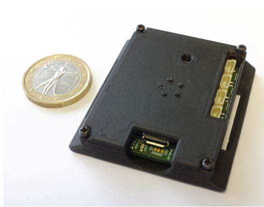

Fig. 5. Audio-400

The Audio-400 extension provides **multi-channel embedded audio/haptic synthesis** for WBTs. A highly integrated form of a dual Teensy Audio Adapter,[4] it provides four channels of high-fidelity synthesis to drive wide-band actuators or headphones. It is based on a Teensy 3.2 microcontroller controlling two stereo digital-audio-converters (NXP STGL5000) and is implemented as a board-on-board PCB. The Teensy Audio Library performs synthesis with help of controller's DSP extension. DSP routing is readily pre-configured through a web-based graphical editor. Our Audio-400 module can operate stand-alone, or be controlled via Qwiic.

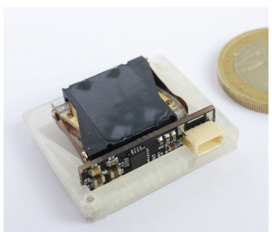

Fig. 6. L5 Tactor, Amp-200

Our primary **tactor** choice are the Lofelt L5 (Sec. 2.1), compactly housed together with the Amp-200 module, a highly integrated DG-Class audio **amplifier** (Maxim MAX98307, 3.3W, Fig. 6). Audio-400 and Amp-200 connect via the same JST SH headers Qwiic uses, thus requiring only a single cable type for all interconnects in the BRIX5 system. We designed a set of **audio adapter** boards (one shown in Fig. 7 (right)). These allow rapid switching between tethered (external signal source, e.g., for prototyping) and untethered operation, optionally allowing simple extension by routing four channels of audio/haptic signals through off-the-shelf RJ45 ethernet cabling. A combination of audio adapter, power, and Amp-200 modules provides a modular, functionally equivalent to the Syntacts [8] system hardware.

3.5 Integration: Power, Housing, Reproduction

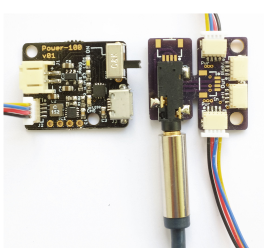

Fig. 7. Power-100, Audio Adapter

Power supply specification varies with application and number of tactors driven simultaneously. The BRIX5 base module's Feathers usually supply up to 600 mA; for applications without base module, we designed a standalone power module (up to 800 mA output power, Fig. 7). We have also successfully used the Smart Prototyping ZIO Battery LiPo Battery Manager (up to 1.35A).

We 3D-printed **housings** for mounting our modules on 1" webbing straps (on an Ultimaker UM3). A shared parameterized CAD model (Siemens PLM SolidEdge) facilitates rapid adaptation to new modules. A two-way hook on the top cover (Fig. 3) allows to affix zip ties for strain relief.

[4] `https://www.pjrc.com/store/teensy3_audio.html`

Small quantity PCB production and assembly has become more affordable, making reproduction of the custom PCBs for BRIX5 possible with moderate technical and financial resources [8]. We will provide the design files for base controller, custom extensions, and parametric housing at `https://opensource.cit-ec.de/projects/brix5`, along with instructions for their reproduction.

4 Application Examples

We have successfully used BRIX5 for applications ranging from playful exploration during teaching to prototype construction for in-situ evaluation. Two examples:

We hosted a one-day workshop, tasking computer science undergraduates (n=15) to "Use BRIX5 to create a system that gives you a new sense." All five student teams finished the workshop with functional prototypes, such as a compass belt and a distance-to-vibration glove. This provides preliminary evidence that BRIX5 enables physical computing beginners to rapidly proceed from idea to proof-of-concept.

On the other end of the spectrum, BRIX5 formed the basis of an adaptable tactile brain-computer interface (BCI) for minimally responsive individuals, supporting a fast-paced development of custom hard- and software in an interdisciplinary, multi-center project. We used BNOs, Audio-400 + Lofelt tactors, and a custom vibrotactile glove (3 LRAs/QuadDRV) to capture movement and provided VT stimuli for a P300-based BCI [3]. The modular and hybrid systems can operate both stand-alone and as part of a larger system, which allowed prototyping and evaluation of one aspect at a time prior to integration [6] for in-situ evaluation. The Arduino-based BRIX5 base controller allowed experimenters to modify firmware aspects independently.

In both cases, access to a large number of existing Qwiic extensions proved invaluable for rapid prototyping.

5 Discussion and Conclusion

Open ecosystems provide tools and methods that begin to fulfill a long-held promise to emancipate, democratize, educate, and empower a broad audience in new forms of technology citizenship [1]. With BRIX5, we present a modular toolkit for wearable VT haptics prototyping, intended to make its technology more accessible. Our hope is to enable more diverse teams to tackle the vertical process of integrating haptic technology into a design, involving hardware, firmware, software, application, and context [6]. Parisi et al. argue for a transdisciplinary Haptic Media Study (HMS), akin to Visual Culture and Sound Studies, suggesting a "sustained attack" on touch media involving a wide range of methods and approaches, escalating in response to touch's unique complexity and multiplicity [7]. We hope BRIX5 can inspire others to share further interoperable building blocks that may enable more critical exploration, novel applications, and large-scale evaluation [10].

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