Re-Thinking Instrumental Interface Design: The MetaBow.

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While extensive research has been conducted on the development and implementation of inertial movement unit sensors for violin bows over the past two decades, most of these new interfaces share a common drawback: their bulky and non-user-friendly design. Despite the advancements in sensor data processing for composition, performance, and pedagogy, interface design remains a critical bottleneck for the real-world implementation of these sensor-embedded devices. Our study introduces MetaBow©, a low-cost, non-intrusive bow frog design that can accommodate either a standard sensor kit or a custom-designed board. This interface eliminates the need for additional physical training and maintains the integrity of traditional violin performance mechanisms. We thus view MetaBow as heralding a new era in Digital Music Interface (DMI) design for the violin family that has the potential for seamless human-computer and human-machine collaboration in music practice and performance.

Keywords

Violin bow interface, MetaBow, MBow, DMI design, transparent HCI

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This article introduces the preliminary research that led to the filing of an international Patent Cooperation Treaty (PCT) application in August 2023. The team involved in the preliminary research presented here included Roberto Alonso Trillo (Hong Kong Baptist University - General Interface Conceptualization and Design), Peter Nelson (Hong Kong Baptist University - General Interface Conceptualization and Design), Tychonas Michailidis (Birmingham City University - Interface Design Consultancy), James Bradbury (University of Huddersfield - MaxMSP Development), Paulo Chiliguano (Queens Mary University - MaxMSP Development).

Introduction

MetaBow addresses the often-neglected significance of interface design in determining a device's real-world implementation and its enduring influence on performance and pedagogy, representing an attempt at reimagining instrumental interface design. The paper opens with a discussion of our user-guided design methodology, an introductory examination of existing literature, and a detailed analysis of the MetaBow interface, which has now undergone 53 design iterations through 5 prototype updates in different versions for violin, viola, cello, and double bass (vimeo.com/579033792 see Figure 1). Focusing on the violin model, we explore how MetaBow's design addresses issues found in previous research and outline our strategy for measuring bow and right-hand motion relative to the linked software environment currently under development. In doing so, we place the MetaBow within the broader framework of Musical Interface Technology Design Space (MITDS), a "conceptual framework for describing, analyzing, designing and extending the interfaces, mappings, synthesis algorithms and performance techniques for advanced musical instruments" (Overholt 2012, 80).

[Figure 1 about here]

User-Guided Design and Real-World Implementation

MetaBow's design drew inspiration from current research on the effect of instrumental modifications on learned performative sensorimotor mechanisms and their resultant impact on performance quality (e.g., Morreale et al. 2018). This relates both to the notions of embodied music cognition (Leman 2008; Loeffler et al. 2016) and to the vision of the instrument as a mediation technology that, through the automation of its relationship to the body, becomes an integral part of the performer's physicality. Our design sought to avoid any alteration in the traditional frog structure. Following Krakauer et al. (2006), we attempted to minimize any disruption to generalized pre-learned existing gestural frameworks in standard violin practice, avoiding the disruption of feedforward patterns. The MetaBow stems from the vision of the instrument not only as a "mechanical object but as a set of performance practices" (Morreale et al. 2018). By taking into account the centrality of the action-sound relationships, MetaBow does not challenge the instrument's recession to the performer's unconscious space, through what has been described as functional transparency (Rabardel 1995). Thus, the interface can be considered as what Dourish (2001) defines, following Heidegger, as a *ready-to-hand* tool.

Our design is player-oriented. Considering retrospective taxonomies for the evaluation of DMIs (e.g. Drummond 2009; O'Modhrain 2011), MetaBow exemplifies newer interface design methodologies, as introduced by Morrealle et al. (2014) in the MINUET framework (see Figure 2). A preliminary discussion of the people (*who*), activities (*what*), and context (*where* and *when*) led to the specification of the technological and design frameworks. The MetaBow targets violin students and performers of all levels. Its design serves as both a pedagogical tool offering live feedback and a performative tool enabling compositional mapping, opening doors to new forms of collaboration (e.g., student-teacher, performer-composer). Users may use the interface during solo practice, performances, group teaching sessions, or ensemble performances. It aims to enhance the performer's learning curve, working as an undisruptive facilitator of traditional learning and performative practices.

[Figure 2 about here]

Previous Violin Bow Interfaces

A theoretical and practical examination of previous bow interfaces ignited our initial research on MetaBow, which was both practice-based, emerging from our performative explorations, and practice-led, as it aimed to generate new knowledge that could transform the analysis and understanding of violin performance. A review of available bow-tracking technologies revealed that most devices were either too costly (Maestre et al. 2007), non-portable (Rasamimanana et al. 2009, Schoonderwaldt et al. 2009), a complete DMI redesign requiring re-learning of the performing mechanisms (McMillen 2008) or had limited accuracy (Rasamimanana et al. 2006). In this study, we have chosen to explore, for the sake of brevity, a selection of representative models designed between 2000 and 2008 that have had significant academic impact (Trueman et al. 2000; Young 2002a; Guettler 2008, McMillen 2008; Bevilacqua 2006). Table 1 provides a schematic overview of sensors, designs (either as an add-on to an existing bow, a bulky redesign of the frog structure, or an attempt to integrate the circuits into a modified design of a traditional bow frog), battery types, output formats, latency, connectivity protocols, sampling rates, and a list of the modifications that each device has made to the standard frog architecture with regards to overall design and weight, balance point (i.e. the distance from the frog at which the weight on each side of the bow is equal), and overall dimensions. In contrast, MetaBow introduces a simple integrated design that resembles a traditional bow frog. Its inertial measurement unit (IMU) embeds a 3D axis accelerometer, gyroscope, magnetometer, pressure sensor, and microphone (used to infer bow-force data) by employing Bluetooth Low Energy (BLE) connectivity. It is powered by a small 100 mAh Li-Po battery and operates through an Open Sound Control (OSC) protocol.

[Table 1 about here]

MetaBow™

MetaBow seeks to address the design shortcomings identified in the aforementioned interfaces. Moreover, we propose that our interface, built upon the framework of border ecosystemic factors as defined by Marquez-Borbon et al. (2018), presents a solution to the durability issues discussed in previous studies. It is important to acknowledge that the traditional design of the violin bow has remained unchanged in Western classical music performance and pedagogy since the late 18th to early 19th centuries (Stowell 1999, 24-26). This historical adherence to conventional bow and violin models may explain the resistance to previous modifications within the established global community of classically-trained professionals, including teaching institutions, orchestras, soloists, and chamber musicians, who have been hesitant to embrace design modifications. The MetaBow, while aligning with the technological paradigms of the hyperbow, hyperinstrument, and augmented violin/bow (Maestre 2007; McMillen 2008), maintains the appearance of a traditional bow. Its shape remains unchanged, and it upholds identical weight balance, responsiveness, and tactility (a formal experiment that evaluates these somewhat subjective elements is detailed in the 'Preliminary User Testing' section below). By incorporating an inner technological capability within a seemingly standard design, it epitomizes a non-intrusive form of transparent collaboration between humans and machines, nesting an inner technological life under an apparently standard design. As a result, MetaBow does not disrupt traditional violin performance or require any form of physical retraining. It can be seamlessly integrated into the practice and performance routines of any player, teacher, or student, demonstrating its potential to transform linked pedagogical and performative practices. By augmenting the technical capabilities of the instrument in a non-invasive manner, we contend that MetaBow can enhance our capacity to track and record gestural data from traditional violin performances, making a substantial contribution to the fields of musical pedagogy and embodied music interaction. In doing so, it bridges the divide between academic research and real-world implementation.

IMU Sensors

Against current alternatives such as motion capture, machine-learning analysis, and video tracking, we argue that the MetaBow's implementation, given its feasibility as a low-cost and user-friendly device, would have the greatest short- and mid-term impact on the development of string pedagogy, performance, and composition. Our initial research explored the implementation of BITalino's R-IoT sensor kit (see https://ismm.ircam.fr/riot/). The MetaBow 1.1 prototype incorporated the R-IoT board and a 3.7 V and 240 mAh Li-Po battery into a custom-designed hollowed 3D printed bow frog. The R-IoT is the 7th generation of IRCAM's wireless sensor digitizing units and embeds a 9-axis digital IMU sensor (LSM9DS1) featuring a 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer. The sensor is attached to the Serial Peripheral Interface port to sample the 16-bit motion data at a high speed. In addition, there are two 12-bit ADC inputs that are compatible with BITalino sensor modules. The R-IoT operates via Wi-Fi connectivity with an OSC communication protocol. We eventually discarded BITalino in view of its large size and weight and the complexity of the Wi-Fi connection mechanism for a non-specialist.

MetaBow's 1.2 prototype integrated a combination of two SensorTile units developed by STMicroelectronics (see https://urlis.net/k1uz2daf): a STEVAL-STLCS02V1 soldered to a modified version of the basic cradle included in the STEVAL-STLKT01V1 kit. The cradle houses a mini-USB battery charger and port, humidity and temperature sensors, and an SD memory card slot and breakaway SWD connector that were removed from the unit. The basic sensor is a small square-shaped Internet of Things (IoT) module that shares features with the BITalino but embeds an 80 MHz STM32L476JGY microcontroller, BLE connectivity, and a nano digital microphone. We employed an OSC communication protocol for data sharing, and the BLE simplified the connectivity and significantly reduced battery size and consumption (see Table 2 for details).

While the unit size improved with the ST models, the resulting MetaBow 1.2 interface remained somewhat larger than a traditional wooden frog. For the MetaBow 1.3 prototype, we designed a smaller sensor board, the MetaBoard©, which contains all the essential components, measures 14 × 27.5 mm, and can be embedded into a standard size frog-housing-design (Figure 3). The board incorporates a 3-axis accelerometer, gyroscope, and magnetometer, nano microphone, microcontroller, a vport for a force-sensing resistor, and mini-USB port used to charge the battery and for debugging and software-related ends. The board has a 4-layered structure with a minimum hole size of 0.15 mm.

[Figure 3 about here]

Housing Design

While the MetaBoard played a crucial role in the development of the MetaBow, its key innovation had more to do with the housing design than with the embedded technology. All iterations of MetaBow's housing unit (adding up to a total of 57) were first developed as 3D models under the guidance of an internationally renowned bow maker, then printed, and collaboratively tested. For the MetaBow 1.1 prototype, we needed to create a hollow frog that could house an R-IoT sensor kit. We had initially developed a rough model (MetaBow 1.0) with the correct upper dimensions to be attached to any violin bow and then focused on the design of the inner housing (see Figure 4). The next phase involved a detailed revision aimed at reducing the total volume of the units. The final MetaBow 1.1 R-IoT housing unit’s final print combined an SLS polyamide black dye matte polished print of the case, with a minimum wall thickness of 0.8 mm to guarantee durability, and a yellow gold plating brass print of the lid (see Figure 5 below). The substantial weight and size of the R-IoT led us to redesign the housing, abandoning the implementation of the R-IoT in favor of the ST Microelectronics' smaller SensorTile IMU.

[Figure 4 about here]

[Figure 5 about here]

Shifting from the R-IoT to the SensorTile allowed us to substantially reduce the MetaBow's size and weight (see Figure 6 for a visual comparison and Table 2 for measurements). The MetaBow 1.2 prototype housed the power button and mini-USB charging and debugging port on the rear part of the lid, and we left a hollow space on the side to improve sound capture through the nano microphone. The top part of the lid included the hole and additional support material for the insertion of the bow's eyelet, which can be easily replaced without damaging the interface. Finally, the areas for the insertion of the mother-of-pearl slide, ferrule, and horsehair mortise were designed for a standard bow rehair. We included an optional specially designed widget to replace the wooden insertion in the mortise as an alternative to the traditional approach for securing horsehair. Figure 7 shows the 3D rendering of MetaBow 1.2, and Table 2 presents a comparison between the 1.2 and previous prototypes.

[Figure 6 about here]

[Table 2 about here.]

[Figure 7 about here]

Our current research focuses on the improvement of several elements of MetaBow's 1.2 (ST version) and 1.3 (MetaBoard modification) prototypes for a new 1.4 prototype, working closely with players and bowmakers to optimize the housing design (see Figure 8). We addressed weight issues by redesigning the lid, removing unnecessary metallic content to make the unit as light as possible, inserting anchoring points to guarantee robustness, and revising the horsehair rehairing channel (see Table 3). We are also advancing the software environment for MetaBow, positioning it as both a performative and pedagogical interface. But before delving into this critical aspect of our current research, let us discuss our strategy concerning the intertwined challenges of bow motion measurement and data processing.

[Figure 8 about here]

[Table 3 about here]

Design-Guided Hardware and Bow Motion Measurement

Our review of existing research led us to reconsider the analytically relevant aspects of the violin's bow and right-hand movements that had to be inferred from MetaBow's embedded technology. The elements explored in previous interfaces include: i. transversal velocity, i.e., bow speed (accelerometer - the speed at which the bow moves across the strings); ii. transverse position, i.e., bow tilt (gyroscope - refers to the bow's deviation from a vertical line to ground level); iii. bow location (using external antennas, resistance wires inserted into the horsehair or an EMF system such as Polhemus); iv. bow force (amount of force being applied to the bow at any given time, measured by a sensor located under the horsehair or by multiple strain gauges, or inferred from an audio capture); v. bow inclination (refers to the bow's angle relative to the ground level); vi. bow-bridge distance (the distance between the bow and the bridge of the violin); and vii. finger pressure (measured with resistive strips placed along the bow-holding areas - the amount of force exerted by fingers when holding the bow) (e.g., Askenfelt 1986, 1989). While MetaBow's design seeks to avoid the disruption to traditional performing techniques, its sensors aim to generate a similar range of data as that of previous interfaces.

Bow Force and Finger Pressure

We infer the bow force from the sound captured through the microphone following Wilmers' (2008) model. Previous interfaces obtained this data using strain gauges mounted along the horsehair (Askenfelt 1989), a bracket insertion into the D-shaped ferrule (Demoucron 2006), strain gauges located at different deflecting bow positions (Young et al. 2007), or the inference of bow force from the pressure of the right-hand's index finger (Paradiso et al. 1997). We used instead the spectral envelope as a function of bow force and bow speed independent of the contact point (see Guettler et al. 2003). A fast algorithm that determines the approximate energy ratio between band-passed (5.0–7.5 kHz) and low-passed frequencies (2.5 kHz) provides an overall sense of bow-force variations.

To measure finger pressure, we inserted a modified version of the Interlink 402 round force-sensitive resistor (FSR) into the finger placement area of the frog's inner structure, under the lateral mother-of-pearl eye. This FSR sends finger pressure data through the board, allowing the system to infer finger force/pressure.

Calibration

Whereas we have inferred bow speed and tilting from the current OSC data stream including gyroscope, accelerometer, and magnetometer values as floating numbers, we have had to propose alternative approaches to the acquisition and visualization of the remaining gestural elements. We are working on an initial calibration mechanism, which remains work-in-progress, that does not rely on an EMF system (Maestre 2007) or the mounting of near-field optical sensors (Pardue et al. 2015). The calibration necessary for the visualization of pedagogically relevant data requires the installation of a second adhesive MetaBoard unit under the instrument's tailpiece. Such a process would allow us to gather and visualize in a detailed three-dimensional framework data related to bow location, inclination, and bow-bridge distance.

Data Acquisition and Processing

At present, MetaBow's toolkit exports metadata including timestamp, audio reference, score reference, and all MetaBoard sensor data into a NoSQL external tool that logs it to a cloud-based database. Although the MetaBow favors quantitative biomechanical movement analysis; we plan to explore the use of machine learning as a way to improve gesture tracking accuracy, developing a qualitative analytical approach that combines elements from Laban movement analysis (see Laban and Lawrence 1947; Maestre 2007) and Bartenieff fundamentals (Hackney 2000). We aim to introduce a new approach for the acquisition of instrumental gesture parameters in a live setting. The future development of the MetaBow interface and its associated software is expected to lead to the creation of an annotated database similar to that proposed for the Gesture Descriptor Interchange Format (GDIF), combining audio and parametric metadata. The GDIF was initially an OSC address space designed to "store all sorts of data from various commercial and custom-made controllers, motion capture, and computer vision systems, as well as results from different types of gesture analysis, in a coherent and consistent way" (Jensenius 2006, 176), allowing for cross-platform and institutional data sharing.

Audio-to-Score Alignment / Score Following

The MetaBow includes an MP34DT05 ultra-compact, low-power, omnidirectional, digital MEMS microphone built with a capacitive sensing element, and an IC interface. It employs a 64 dB signal-to-noise ratio and –26 dBFS ±3 dB sensitivity with an AOP of 122.5 dBSPL and a PDM output. The microphone enables a simple implementation of an audio-to-score alignment module, providing real-time alignment between sounds and a given score, into the performative and pedagogical Max Patches and Touch Designer patches that we are currently developing.

Over the past two decades, the vast amount of research on this topic (see Orio et al. 2003) has led to the creation of systems capable of detecting minor errors, skips, and mistakes (see Nakamura 2014, 2015). Most of these combine the exploration of hidden Markov models and MIDI or musicXML scores. One of the most salient projects in the field, IRCAM's score follower, became the open-access Max Patch Antescofo, a modular polyphonic app-like score following system (see https://www.antescofo.com). Further research in this area has been conducted as part of the TELMI project through the ViolinRT real-time play-along prototype (http://telmi.upf.edu) and the i-Maestro project (Ng and Nessi 2008).

Sound variability is a critical issue in analyzing a real performance setting, a complex dimension that relates to elements such as acoustic variations (e.g. spectral variations, background noise), temporal fluctuations, performance errors, and, during practice sessions, the repetition or skipping of specific sections. On this basis, we have implemented a modified and updated version of IRCAM's Antescofo into our Max MetaBow Toolkit (https://github.com/robertoalonsotrillo/MetaBow-Toolkit) as a starting point to explore future modifications that may improve the mapping and data visualization modules that will be part of the interface's software environment at a pedagogical and performative level.

IoT Hubbing

A further significant element of our current work is the implementation of an IoT hub-based system for distributed data logging. We have considered some of the key IoT cloud solution providers (Microsoft's Azure IoT Hub, Amazon's AWS, and Google's Cloud IoT) and are currently working on its development. Our mid-term aim for MetaBow's commercialization is to use IoT hubbing both as a means to explore different approaches to networked performance and, more importantly, to generate a global database of right-hand objective gestural data. Such a database would allow us to gain, through a machine-learning approach, new conditioned or unconditioned (organized by level, age-range, location, etc.) insights into the current gestural practices of violinists at the worldwide level.

Software Environment

We are currently developing a software environment at the aforementioned two key levels: performance and pedagogy. We have developed a MaxMSP package (MetaBow Toolkit, see link above) that, while based on existing research (e.g., Bevilacqua et al. 2005; Schnell et al. 2005; Fasciani et al. 2012), provides a clean and intuitive graphical user-friendly interface for both MAX experts and novices (see Figure 9). The MetaBow Toolkit comprises a scalable modular approach to continuous and selective multimodal gestural mapping and an initial calibration routine. We are also working on different approaches to data visualization aimed at using MetaBow as a tool for live pedagogical feedback that may be easily integrated into standard practice and teaching routines. Our present research explores both the combination of Max/MSP/Jitter and the use of TouchDesigner as core software frameworks.

[Figure 9 about here]

Preliminary User Testing

In September 2022, we conducted a preliminary user testing session in Madrid, Spain, with a professional quartet. We invited the quartet to rehearse and perform Shostakovich's String Quartet No. 3 using MetaBows and a customized reactive gesture-based visual mapping model developed in TouchDesigner. The session aimed to evaluate the device's responsiveness, ease of use, and potential usefulness from the performers' viewpoint, rather than assess the aesthetic quality of the visual framework specifically created for the event. Following the rehearsal, we presented the quartet with an anonymous questionnaire, adopting a modified version of the expanded technology acceptance model (TAM2, see Venkatesh & Davis 2000) with a 5-point Likert Scale (see https://rb.gy/gjtcik).

TAM (Davies 1989) outlines a three-stage process for technology acceptance starting from external factors, moving through cognitive and affective responses, and leading to actual use behavior. It is based on elements such as perceived ease of use, perceived usefulness, and behavioral intention, with the first two directly impacting use behavior. TAM2, an extension of TAM, introduces additional elements such as subjective norm (perceived social pressure influencing technology use), image (enhanced status from technology use), job relevance (technology's applicability to a specific job), output quality (quality of technology's results), result demonstrability (tangible benefits of using the technology), experience (familiarity with the technology), and voluntariness (freedom in choosing to use the technology). Each plays a significant role in influencing technology acceptance and usefulness perceptions. For instance, job relevance indicates how applicable technology is to one's job, directly affecting perceived usefulness and moderated by output quality

In this particular study, elements such as subjective norm (question 8), job relevance (7 and 12), result demonstrability (15), and experience (5 and 6) have been specifically included to evaluate technology acceptance, helping in comprehensively understanding the factors influencing judgments about technology usefulness. Table 4 introduces an average of the results across the quartet members, followed by the average per area of evaluation using the proposed 5-point Likert scale.

[Table 4 about here.]

Overall, the performers praised the MetaBow for its ease of use and broad utility and described the device as comfortable, lightweight, and user-friendly. Its motion detection technology was highlighted as innovative, enhancing both creativity and insights among musicians. The MetaBow, as underscored by its high rating in pedagogical potential and its relevance to teaching, seems particularly advantageous for educational settings. While there were mild reservations concerning its fit for professional performances and overall market necessity, the feedback largely tilts towards optimism, indicating that with minor refinements, the device could be a game-changer in its domain.

Conclusion

This paper outlines our innovative approach to designing a violin bow frog interface, aimed at overcoming the usability constraints observed in earlier, bulkier, and less ergonomic models. Beyond the violin prototype, MBow Ltd has expanded the range to include bows for viola, cello, and double bass. While recognizing that its design is a minor part of MetaBow's ongoing development, we assert it as a crucial foundation for forthcoming related research. Metabow's success depends on our capacity to establish a broad community of practice through an interface ecology that intertwines its performative and pedagogical dimensions and thus ensures its seamless use as both a learning and playing tool. The short- to mid-term commercial launch of this product will serve as a practical test for this community framework, sparking further research into its applications and potential to revolutionarily influence string pedagogy and performance.

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