MetaFlute: A Wearable Interface for Gesture Detection

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ABSTRACT

For four decades, researchers have been creating flute hyperinstruments, either by mounting sensors to the flute body or human body, or by creating wind-like instruments embedded with sensors. Primarily, the desire has been to extend and/or enhance an artists performance technique. More recent technologies provide near real-time interaction, rich datasets and are getting easier, faster, and cheaper to use; therefore, previous flute hyperinstruments are becoming more obsolete. A motivation for designing this newest flute hyperinstrument stems from a desire to gain a deeper understanding and awareness of the performative gesture features that occur during flute performance. This paper presents the extensive iterative process of upgrading previous components towards the motivation. The acquired gesture features are used as part of a larger project 1) to improve real-time, audio-only signal processing techniques and 2) to gain an understanding of ancillary gesture features present during flute performance.

1. INTRODUCTION

The *MetaFlute* is a framework created by the author to explore and to gain a deeper understanding and awareness of the performative gestures that occur during flute playing. One component is a custom hardware system designed to capture gesture features from both the musician's body and their instrument. The second component includes two custom software analysis techniques. The third component is a proposed animation of the acquired performance parameters. This paper describes the development of the hardware interface of the *MetaFlute*.

The motivation of this research is to use technology to gain a deeper understanding about some of the musically expressive techniques present in flute playing. To that end, this interface serves two purposes: 1) to improve real-time, audio-only signal processing techniques and 2) to gain an understanding of ancillary gestures present during flute performance. The *MetaFlute* framework could help with better understanding of the nuanced performance techniques, within the context of musical expression.

The iterative design process presented in this paper is based on past research, *a priori* assumptions, and empirical knowledge of the physical attributes present in flute performance. A comprehensive literature review of previous flute hyperinstruments, from which this research is drawn, upon is available in [1] by Siwiak *et al.*.

1.1 Design Considerations

Jensenius *et al.* [2], Cadoz *et al.* [3], and Wanderley *et al.* [4] all discuss various interpretations of *gesture* and *movement* with respect to music. They delineate several motions present in instrumental performance, two of which are focused upon herein. *Sound-producing*, or instrumental, gestures occur when the body's movements directly create sounds, such as fingers on keys. *Sound-facilitating*, or associating, gestures are ancillary performance gestures, such as those observed at the end of the flute as it moves.

The *MetaFlute* is embedded with sensors to extract determined performance gesture features that occur during music production. The four key gesture features in this research are change in exerted breath information, change in applied pressure from two balancing fulcrum points, the flute's continually changing position in three dimensional space, and the intricate movements from fingers and forearm muscles. The *sound-producing* gesture features are the breath information and forearm muscle movement. The *sound-facilitating* gesture features are the change in fulcrum pressure and spatial orientation of the flute.

The design specifications for *MetaFlute* hardware interface (as determined in [1]) include acquiring high-rate multidimensional data (ranges to be confirmed through the iterative process), implementing a low-profile mounted interface (such that integration does not hinder natural playing ability), wireless capability (such that a musician is not tethered to a computer), adaptability (in terms of easily replacing or adding sensor components and electronics components), and generalizable design (such that other researchers can easily replicate this design).

2. DESIGNING A WEARABLE INTERFACE

2.1 Circuit Boards

2.1.1 Printed Circuit Board

The flute body is approximately 71 cm $\times$ 0.2 cm, which is important to consider when designing a circuit that requires attachment of various sensors (such as orientations sensors and force sensing resistors). The weight, construction, connections, sensors, and obtrusiveness of the circuit also inform the interface's design considerations.

This research began by recreating prior flute hyperinstruments ([1]). However, conventionally designed printed circuit board (PCB) technology protrudes from the instrument. There are long strands of wires that often obstruct the ability to naturally play the instrument. Additionally, through-hole connections are not ideal for an interface meant to be only a few millimeters tall; the solder scrapes against the flute body. This could be solved with padding or a hot glue layer, however that adds to the profile of the interface. This does not yield a low-profile integration.

Several wires were required for connecting each sensor to the prototyping board. As each sensor requires multiple connections, the interface was delicate and vulnerable to damage. It also proved challenging to mount the PCB to the flute and to mount the sensors to the instrument, given their rigidity and protruding wires. Finally, the aesthetics of the interface were described by users as "displeasing," which refers to the electronics being exposed rather than neatly contained in a production-quality enclosure. However, this PCB did facilitate the testing of components (such as the sensors, discussed below) so a more ergonomic and mechanically-robust version could be developed using flex circuit material.

2.1.2 *Flexible Circuit Board*

The second iteration of the *MetaFlute* hardware attempts to address issues from the first iteration, specifically the protruding wires and the mounting issues of the circuit and the sensors to the instrument, by using a flexible printed circuit board (FPC). FPCs are professionally manufactured PCBs that act both as a circuit and a mounting surface for electronic components, thus alleviating the encountered challenging task of sensor mounting. They significantly reduce wiring and cabling, are lightweight, and are low-profile [5].

Figure 1. Populated Flex Circuit compared to the Flute

The dimensions of the constructed FPC are 45 cm $\times$ 2.77 cm, as allowed by the manufacturer's specifications and the dimensions of the largest component – the XBee (discussed further below). This size constraint is 26 cm too short for this research (as sensors were required at both ends of the instrument). The FPCs are fragile, so connecting two together is undesirable. Additionally, much like its predecessor, the PCB, the width still protruded from the instrument. However, it was slightly more manageable during music production (as observed by the primary investigator). This FPC (pictured in Figure 1) was designed for through-hole connection, rather than surface mounted connection, as required by the chosen DIY sensors. However, surface mounted components could be considered in future iterations, as they are low-profile and eliminate some wiring necessities.

Several caveats to flex circuits include their length limits, lack of robustness, high manufacturing expense [1] , and mounting difficulty. Additionally, FPC material is particularly susceptible to heat damage, which means soldering can take place only once. This delicacy also means DIY break-out boards place a significant strain on the FPC, as they are too heavy. In retrospect, solder pasted, surface-mounted components might have yielded slightly more successful results, however reprinting a new FPC was cost prohibitive. In their current state, FPCs are not ideal for the *MetaFlute*.

2.1.3 *Wearable Circuit 'Board'*

The final iteration for the *MetaFlute* preserves the flexible printed circuit board design scheme and electronics components, while eliminating some of the FPC's shortcomings. This version inherits the approach to electronics and circuit design that wearable technology has adopted. Wearables integrate technology into daily life to provide "sousveillance", or recording of activity from a small device, such as activity monitors, smart watches, or tiny communication gadgets [6]. This more gentle circuit (shown in Figure 2) can be smoothly integrated into the practice routine, limiting hindrance on natural playing ability, while giving the researcher rich gestural feature information. The final version of the *MetaFlute* is a long, thin (67 cm $\times$ 6 cm $\times$ 0.15 cm) piece of durable, non-conductive black fabric sewn with 2-ply stainless steel conductive thread [2] , which replaces the wires and trace lines.

Figure 2. Wearable circuit

Unlike traditional PCBs, modifications of the sewn FPC connections and components can be easily accomplished, while still maintaining its stability for multiple uses. The wearable circuit is constructed with the desired length, a comfortable fit (as described by study participants), and a "pleasing aesthetic' (compared to the "electronics feel" of exposed sensors and multiple wires in the first two iterations). Additionally, the low-profile design of the embedded electronics (while also eliminating the need for wires) makes this ideal for unobtrusively acquiring the necessary gesture features. It also provides a generalizable design from which future researchers to replicate, as well as implement the design for other instruments. The physical design of the wearable circuit provides a solid base to attach

[1] This particular design costs \$100 NZD per FPC, with a minimum order of 10 units, for a total price of \$1000 NZD

[2] https://www.adafruit.com/product/640

appropriate sensors and an Arduino prototyping board, as well as a wireless transceiver.

3. DATA ACQUISITION

3.1 Breath Pressure

The two primary ways the excess air flow can be measured using non-invasive means are via a breath pressure sensor or a small capsule microphone. This section describes using both means for acquiring breath pressure at the embouchure during flute playing.

3.1.1 Breath Sensing via Commercial Sensor

Iterating on the work by Birnbaum [7], daSilva [8], Scavone [9], Fels [10], and Romero [11] (using a pressure sensor to capture the excess air flow when playing flute) and testing the viability of this sensor against that of a microphone, the second iteration of the *MetaFlute* includes the SparkFun MS5803-14BA pressure sensor break-out board. [3]

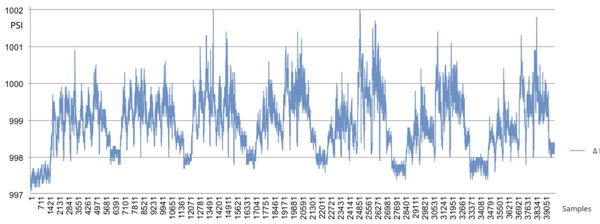

Figure 3. Breath Pressure from Sensor

During playing, the pressure readings (shown in Figure 3) from the change in altitude (as excess air pressure is observed) depict changes in energy over time (in samples), which represent either a note onset or a vibrato warble, as expected. However, this sensor is particularly susceptible to damage from the humidity and direct pressure from the air stream; it was replaced three times over the course of nine months. While sensitive (in terms of resolution and accuracy) for detecting changes in energy with respect to air pressure, the delicate nature of this sensor warranted another solution.

3.1.2 Breath Sensing via Lavaliere Microphone

Iterating on the work by Pousset [12], Yunik [13, 14], and Ystad [15, 16] (using a microphone to capture the excess air flow when playing flute), a more viable solution was found in a lavaliere microphone placed within centimeters of the tonehole. The Line 6 wireless lavaliere microphone [4] observes the mouth and tongue sounds present during flute playing, as well as the amplitude of the excess air stream energy (as seen in Figure 4, which exemplifies the breath content as dark blue shadings). It acquires frequency information (shown as the yellow-colored energy at various frequency bins, over time); however, due to its close proximity to the tonehole, this is not a suitable means for pitch tracking, as the audio signal is over-saturated. Its superiority from the other approaches stems from the microphone's robustness and its acquired high-quality signal.

[3] https://www.sparkfun.com/products/12909

[4] http://www.rockshop.co.nz/shop/line6-xdv35l-lavalier-24-bit-digital-wireless-microphone-system-with-beltpack.html

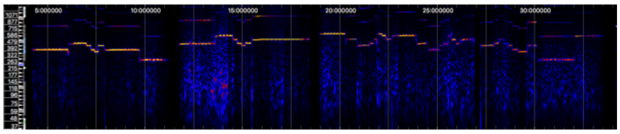

Figure 4. Breath Pressure from Microphone

3.2 Forearm and Finger Muscles

The forearm muscles (including the arm, the wrist, the hand, and the fingers) of both arms are an important physical feature to consider when observing performance gestures. When properly coordinated, these muscles support rapid, fluid movements. Traditional glove interfaces [17, 18] can track finger movements, however, due to the intricately close and subtle finger movements needed to play the flute, a glove interface would impede natural playing ability. Additionally, the signal-to-noise ratio (above standard sensor noise) would likely mask subtle movements.

A second possibility for tracking finger movements would be to outfit the flute keys with sensors, such as miniature FSRs or magnets with Hall effect sensors. The flute's hand-crafted mechanisms make using these sensors a challenging option. Additionally, it is invasive to ask a musician to modify an expensive instrument.

A third possibility for tracking finger movement is using video motion capture. However, motion capture, while passive, is a difficult solution to implement for the flute. Several methods were prototyped, including Leap Motion, fiducial tracking, blob detection, and infrared, however, the flute's reflective surface proved very difficult to counteract. This issue has yet to be solved, and spray-painting the flute a matte color for motion capture to succeed is not viable.

3.2.1 Myo Armband

The Myo Armband [5] provides an appropriate solution for tracking forearm muscle movement, as well as for measurements not yet considered – the equilibrium, or net, forces of the muscles. This black box device includes wireless transmission of data from its eight steel medical-grade surface electromyography (sEMG) sensors, an IMU, and haptic feedback. [6]

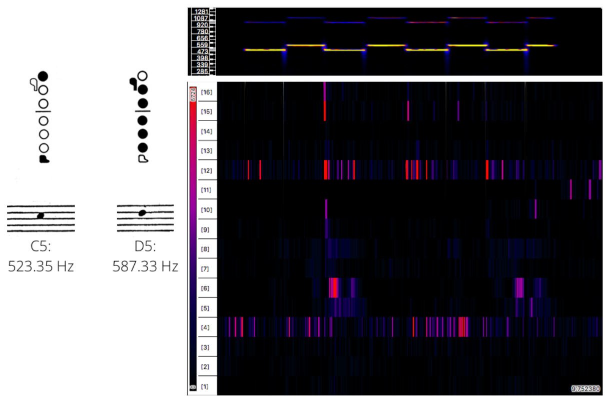

Figure 5. Myo readings (8x2) of alternating note pattern between C5 and D5 against the spectrogram representation of the audio signal.

[5] https://www.myo.com/

[6] https://www.myo.com/techspecs

In order to observe the both forearm's muscle movements, two Myos were acquired, and custom software was designed to capture the eight EMG streams from each device. Using two of these devices gives information about muscle tension and finger movements – the forces of the muscles. This data describes movement intention, by sensing electrical nerve impulses before they are translated into muscular contractions, seen in Figure 5.

3.3 Balancing Points of the Flute

The flute is balanced at three fulcrum points (as seen in Figure 6). These points are *A* the lower lip and chin against the lip plate, *B* the left pointer finger (between the first and second knuckle) against the flute body, and *C* the tip of the right thumb underneath the flute body. This three-point balancing allows the remaining fingers to move in a free and fluid motion, encouraging agile movement. Force sensing resistors (FSRs) are used to detect the two easily accessible and least intrusive contact points, *B* and *C*. Any potential sensor at *A* would greatly interfere with sound production, as this is where the flutist creates the embouchure and forms a stable coupling with the flute.

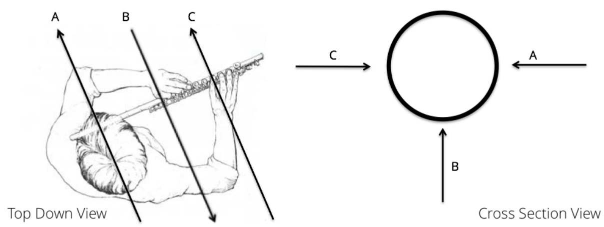

Figure 6. Balance points of the flute

3.3.1 Traditional Force Sensing Resistors

FSRs [7] are often used for measuring change in force, applied pressure, or weight. They are inexpensive, accessible, and suitable for this research, as they detect changes over time. From this information, it can be determined whether or not a flutist is correctly holding the instrument (by applying constant pressure to the contact points). Incorrect handling, such as a lack of required pressure, could impede dexterity and consequently affect playing ability.

However, there are some issues with traditionally manufactured FSRs, including their rigidity, constrained size, fragile connectors, and eventual loss of range with excessive use. Over time, as pressure is continually applied to the sensor, the spacing between the two substrates reduces; the range of resistance diminishes, thus yielding them ineffective and requiring replacement. "Because an FSR's operation is dependent on its deformation, it works best when affixed to a support that is firm, flat, and smooth. Mounting to a curved surface (such as a flute) reduces measurement range and increases resistance drift." [8] Additionally, the available, predetermined sizes are incorrectly shaped for our purposes. Since the FSR's rigidity is uncomfortable for long-term playing, a softer, more generalizable FSR design is sought.

[7] https://learn.adafruit.com/force-sensitive-resistor-fsr/overview
[8] http://www.sensorwiki.org/doku.php/sensors/force-sensitive_resistor

3.3.2 Creating Custom Force Sensing Resistors

Seeking to improve upon the physical design of the traditionally manufactured FSRs, a custom, wearable solution is explored. By creating custom FSRs, they can be of any size and shape. The FSRs designed for the final version of the *MetaFlute* (detailed in Figure 7) include non-conductive black fabric, Velostat, conductive thread, and conductive tape. The responsiveness of the custom FSR is equivalent to that of a traditionally manufactured FSR.

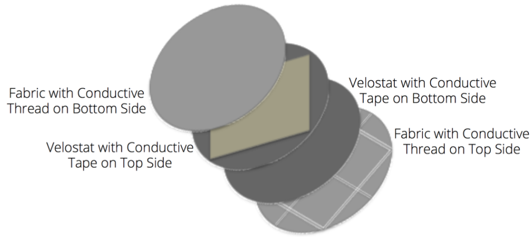

Figure 7. The custom FSR layers, including Velostat, conductive thread, and conductive tape.

The fabric allows for comfortable interaction with the sensors, and the Velostat, [9] conductive thread, [10] and conductive tape. [11] re-create the response of traditional FSRs [19, 20]. The inner sides of both fabric pieces have conductive thread. The outer sides of both Velostat pieces have conductive tape. The conductive thread meshes with the conductive tape (on both sides of the Velostat) as pressure is applied to the sensor.

3.4 Flute in Three Dimensional Space

In order to detect the flute's position and orientation in three dimensional space, this research extends the work of Palacio-Quintin [21] and Scavone [22] and explores the use of a 9 degrees of freedom inertial measurement unit (IMU). Using an IMU to extract the measurements of non-gravitational acceleration, rotation with respect to gravity, and the strength and direction of a magnetic field, the flute's spatial orientation can be calculated.

3.4.1 SparkFun Sensor Stick

The first two iterations of the *MetaFlute* use two SparkFun Sensor Sticks. [12] The Sensor Sticks were placed at opposite ends of the instrument. One of the reasons for using two IMUs in tandem was to determine whether using the headjoint-mounted IMU would expedite and/or alleviate constant need for sensor re-calibration of the footjoint-mounted IMU. [13]

However, after gathering data and testing this approach in two iterations, it was determined that using two IMUs did not help eliminate the need for constant sensor re-calibration. Additionally, the task of sensor fusion on this sensor (using data from multiple sensors and algorithmically extracting information, such as orientation in three dimensional space) proved difficult to accomplish in real-time.

[9] https://www.adafruit.com/product/1361
[10] https://www.adafruit.com/product/640
[11] https://www.adafruit.com/product/1656
[12] https://www.sparkfun.com/products/10724
[13] Sensor calibration improves the precision and responsiveness of the IMU, otherwise there could be errors such as drift in yaw when roll

3.4.2 Adafruit Absolute Orientation Sensor

The newer Adafruit BNO055 Absolute Orientation Sensor includes an ARM processor to "abstract the sensor fusion and real-time requirements" and to supply useful real-time orientation data. [14]

The sensor, placed on the footjoint of the flute, is able to accurately detect pitch, yaw, and roll, which is useful for determining the flute's spatial orientation in real-time. This facilitates capturing physical gesture features, which are natural attributes displayed by flutists of all ages and levels of expertise.

4. COMMUNICATIONS

4.1 Arduino Fio Platform

The Arduino Fio board [15] was used for rapid prototyping purposes. It is intended for wireless applications, [16] which is required by this research. Its appeal included numerous input pins, wireless capability, weight, and long, thin design. However, while this model was suitable for prototyping, it was necessary to minimize the surface area and the weight of the electronics.

4.2 Adafruit Pro Trinket Platform

Adafruit's Pro Trinket (3V) [17] is used in the second and final version. It is a newly available prototyping board that is smaller and lighter than the Arduino Fio, which are preferred features for the *MetaFlute*. It is similar to the Fio, using of the Arduino software, making the transition between the two prototyping boards consistent.

4.3 XBee: Wireless Communication

An important contribution to the research into flute electronics is our desire for the flutist to perform free from wired connection to a computer. Existing interfaces and devices often communicate with a computer via a USB cable, tethering the musician to a small performance space (and thus, hindering natural playing ability). The XBee wireless antennas provide untethered communication between the interface and the computer.

5. OBSERVING PERFORMATIVE GESTURES

The system diagram of the final iteration of the *MetaFlute* is illustrated in Figure 8. It illustrates how the wearable sensor (containing two embedded custom force sensing resistors and an embedded absolute orientation sensor), two microphones (a lavaliere microphone to observe breath and a room microphone to capture the flute audio signal), and two Myo armbands (for detecting change in forearm muscle movements) comprise the gesture capture system. The dotted lines represent wireless communication.

[14] https://learn.adafruit.com/adafruit-bno055-absolute-orientation-sensor/overview

[15] https://www.sparkfun.com/products/10116

[16] https://www.arduino.cc/en/Main/ArduinoBoardFio

[17] https://www.adafruit.com/product/2010

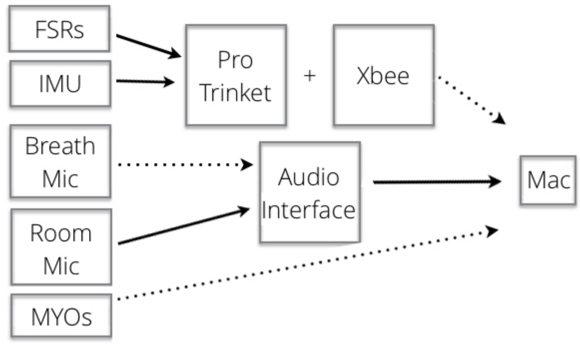

Figure 8. Final System Diagram

6. DISCUSSING THE WEARABLE INTERFACE

The wearable version of the *MetaFlute* hardware interface achieved the primary goals established throughout the iterative design process of minimally invasive capture of four key performance gestures prevalent in during flute playing.

- The flutists recruited for the data capture user study enjoyed using and interacting with the *MetaFlute* hardware interface.
- The gentle nature of the wearable circuit design is a comforting interface that musicians are more likely to accept and use, especially with expensive instruments.
- The wearable interface's profile does not impede or distract the musician from natural playing ability.
- The wearable is simple to hand craft, so custom sizes can be created for most traditional instruments.
- The custom FSRs performed equal to, in the case of ranges, and better than, in the case of ergonomics, traditionally manufactured FSRs.
- The lavaliere microphone provides audio frame rate breath information.
- The *MetaFlute* [18] hardware interface produces a rich set of gesture feature data, which can be used to analyze musically expressive performance techniques.

7. FINAL THOUGHTS

This paper presented the iterative process for designing a wearable interface for observing the performance gesture features that are present during flute playing. By identifying the gesture features that contribute to music production and creating a measurable means of quantifying them, the development of a analysis software [19] to study these features can be achieved.

The performative gesture features that relate to note excitation, namely breath pressure and forearm muscle movement, are used for observing events directly related to note onset. The breath pressure data exhibits steep changes

[18] "Tailored for your instrument."

[19] This is achieved in a forthcoming paper and is outside the scope of this publication.

in energy, which can be used to observe note onset, vibrato, and occurring embouchure sounds. The forearm muscle movement data describes how muscles are in a constant state of engagement during music production, so subtle changes in finger movements are amplified in order to observe movement intention prior to note excitation (as shown above in Figure 5).

This research also studies the performative gesture features related to ancillary movements, namely the applied pressure at the instrument's balancing points and the instrument's position and orientation in three dimensional space. These gesture features do not directly influence music production, however they do impact musical expression and overall performance technique. [20]

The analyses of these two groups of movement data, which is outside the scope of this paper, is discussed in a forthcoming research paper. The analyses processes fuse the gesture data and the audio data used towards understanding various performance techniques (such as some of the quantifiable aspects of musical expression). This data has further implications, such as for extending performance technique and for giving composers and other musicians a higher degree of understanding about salient performance gesture features present during flute playing.

We hope that other researchers may benefit from the in-depth observations concerning circuit design, DIY sensor choices, and software engineering in future research, and might apply this knowledge to other instruments. The implications of gathering such a plethora of data are far and wide reaching. A greater understanding of performance technique has many benefits for researchers, performers, and composers.

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