The Music Bluetooth Controller:

An Intersection Between Technology and Music

Lydia Wu

A Senior Thesis submitted in partial fulfillment
of the requirements for graduation
in the Honors Program
Liberty University
Spring 2022

Acceptance of Senior Honors Thesis

This Senior Honors Thesis is accepted in partial fulfillment of the requirements for graduation from the Honors Program of Liberty University.

____
Feng Wang, Ph.D.
Thesis Chair

____
Young-Man Kim, Ph.D.
Committee Member

____
David Schweitzer, Ph.D.
Assistant Honors Director

____
Date

Abstract

The modern musician faces a new challenge: how can technology be used to enhance a performance? This thesis documents the development of a Bluetooth remote controller that will aid today's performing musicians by interacting with a digital display (e.g., an iPad) to flip musical score pages remotely. At its core, while mimicking a Bluetooth pedal (the current industry standard), this device attaches to the musician's hand. In its pilot stages, the device has been referred to "MBC" (Music Bluetooth Controller).

THE MUSIC BLUETOOTH CONTROLLER:

An Intersection Between Technology and Music

Introduction

The modern musician faces a new opportunity: technologically enhanced performances. A wave of technological advancement has inspired this landscape, particularly in the electronics industry, as remote controllers, interfaces, and sound systems continue to improve functionality, decrease cost, and become more physically beautiful. In this Honors Thesis, a Music Bluetooth Controller (MBC) is proposed that, at its core, has the same functionality as a Bluetooth pedal (the current industry standard [1], [2]), but will attach to the musician's hand.

Purpose of MBC

The Music Bluetooth Controller (MBC) exists to communicate wirelessly with an electronic score reader (i.e., an iPad) to turn pages forward and backward using two buttons. The controller will attach to the musician directly, avoiding contact with a musical instrument, the floor, or another surface. Foundationally, this device will be an aid to musicians in both practicing and performing environments.

A Myopic Literature Review

To contextualize the significance of MBC, it may be valuable to superficially understand Bluetooth and Internet of Things (IoT) technologies. Additionally, the current market is loaded with expansion potential because devices are being more specialized for consumers—the foundation of a clicker can be repurposed into a camera button, a PowerPoint remote, and more. Therefore, review of available resources for digitally aided musicians will create context for the development and release of MBC to the market and the practice room.

Bluetooth and IoT Technologies

A relatively nascent field of study, the Internet of Things (IoT) at its core exists to create connections. These connections are often between remote devices that stretch long distances and communicate via frequencies, whether in the form of a humanly observable wave (i.e., sound) or a frequency that is much smaller (i.e., radio). One form of exchanging data is Bluetooth, a wireless technology standard that relies on a set range of frequencies (in Hertz) to transmit information. Developed by the Bluetooth Special Interest Group (SIG), Bluetooth "aims to become the best alternative to the huge number of standard wireless technologies already existing and widespread on the market" [2, p. 2898].

IoT is still rapidly growing as engineers work to address the demand for faster, cheaper, smaller devices that accomplish greater tasks [3]. By eliminating physical components, namely the wire, Bluetooth beautifully supports the cross-continental web of IoT devices that are approaching innumerable amounts. These generic circuits couple with unique sets of components and code to fulfill diverse system requirements.

Supporting the hardware components that define IoT, cloud computing has become a necessary skill. "Increasing demands for location-based services require accurate wireless indoor location information" [4, p. 1]. Cloud-based ideology asserts that information can be readily communicated and available if suspended in perpetual motion in a "cloud" of transmissions, houses in large data warehouses that are managed, accessed, and referenced from multiple clients. "Small, compact, and embedded sensors are a pervasive technology in everyday life… Wireless transmission plays a key role" [2, p. 2898].

There is an observable potential for wireless technologies in the modern era of the industry. Demonstrated in [5] and [6], devices designed for consumer applications are limited and widespread, not utilizing full IoT capabilities.

The Current Musical Performance Controller Market

Great strides in the market have led to compelling guidelines on producing wireless modules. As seen in [2]- [4], and [6], new markets for human-centered design are quickly growing. The chief driver of this expansion is an awareness of the public to desire self-quantification, tracking behaviors, patterns, and habits to gain knowledge on health, efficiency, productivity, or more abstract concepts like happiness.

There is a current patent out that presents a beautiful overview of the objective of a more generic form of MBC. In [7], Lo details the intention of creating as broad a unit as possible in functionality, focusing instead on low-power aspects instead of application. This current style of innovation, trusting more in creating scalable designs than niche products, has left a gap for custom human-based design. It is undesirable to produce a unit that drains itself and equally distasteful to create a device that kills its master (i.e., the tablet with sheet music on it), especially during a performance. In this way, device-to-device recognition of control is paramount. This can be taken a step further, as MBC can be built on this knowledge to interface musician-to-musician, pupil-to-professor, performer-to-audience in unique, engaging ways. Current standardized architecture provides flexibility to the communications process, from delays to timers; however, this flexibility can make communicating between devices difficult, as it is a challenge to synchronize one device’s clock with another’s to allow for the instantaneous transfer of data.

Method

The development of MBC stretches over almost eight semesters of head-scratching, yet the outputs do not attest to such musings. The heartbeat of this project may be appropriately understood as, “throw many things against a wall, get tired for a long period of time, and then rinse and repeat after a ripple of inspiration.” Such a cycle is marked to have happened in three waves.

The Ideal Design

Before following the lifespan of MBC, it is valuable to summarize the characteristics of an ideal MBC, motivated by the desire to push continued work and contextualize the rest of this section. This system will fit comfortably on any adult musician’s hand, regardless of gender, race, or instrumentation. MBC will operate via a battery pack and Bluetooth (or equivalent connectivity), rendering it as a wireless device. Lastly, MBC will have the following functionality at a minimum: wireless page turning back and forth, microphone data storage and subsequent analysis for pitch correction and habit, IMU data storage and subsequent analysis for hand/body posture, recharging, and an on-off mechanism for power utilization.

The Initial Design

The initial drive to realize MBC came from a slew of comments about performance distractions in the current industry standard for modern performing musicians: the Bluetooth pedal. Usually a large block, it sits on the stage and interfaces with the iPad or other reading device. It is a discrete unit, and the user will step on it to trigger a signal that flips pages on a sheet music display. While not customized to the instrument (i.e., universal for any performer), it provides bulk, distraction, and stress in managing another component in an already overwhelming situation of high-pressure performance.

To address this niche need, MBC was conceptualized as a device that would attach directly to the musician's instrument, eliminating a separate element, the floor/pedal visual factor, and the stress of a far-away unit that could be missed upon execution. Brainstorming the unit led to thoughts on different adhesive materials to stick to the instrument, but that led to complications of material interaction with metal versus wood versus polymers. Because instruments are so distinct in their material makeup, it would be difficult to make a universal adhesive for any woodwind instrument, let alone instruments in other families. In addition, models of instruments are often custom-built for the performer, or else have different sizing depending on brand, class, and age.

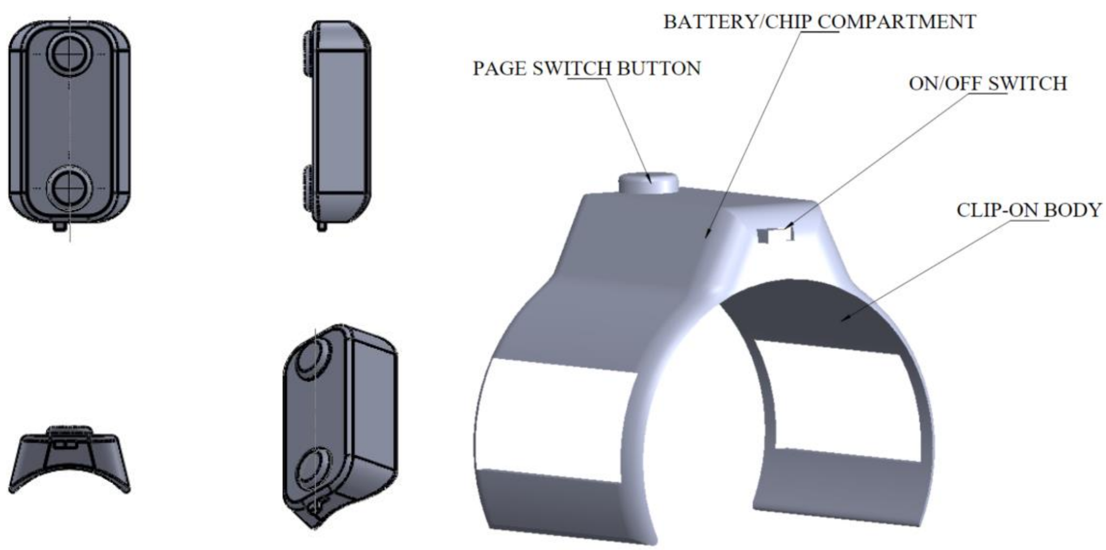


Fig. 1 First Designs of Instrument-Based Device

The first concept was created with the flute in mind. With rounded edges and a grove for potential adhesive, it hosted a shell big enough for a standard printed circuit board (PCB), two user buttons, and a coin battery or power source equivalent. It spanned about two inches in length, but the board inside was not designed functionally, only conceptually. This led to a failure in testing. Different manifestations of a “clip-on” device were created to address various design flaws or strengths, as well as to potentially eliminate the use of adhesive altogether.

These designs were flawed in other respects: (1) the size was not conducive to a working board designed from a novice perspective; (2) the arms would degrade with use; (3) the arms could scratch or damage the body of the flute to which they are attaching.

Iteration Two: A Reimagination

The issue of cross-sectional utility continued to plague the first concept: without re-imagining the basis of the design, a different device would need to be catered to each instrumentation, potentially each instrument itself. The second iteration confronted this dilemma by shying away from interacting with the instrument altogether.

A Hand-Centered Design

The design, as seen in Fig. 2, shifted to a glove style. This would stretch to fit on a user’s hand; while more visually obtrusive, the trade-off of scalability was well worth any visual misgivings. The design was imagined to either exist as a pointer-finger ring or a full glove, and it would expose the fingers for easier mobility.

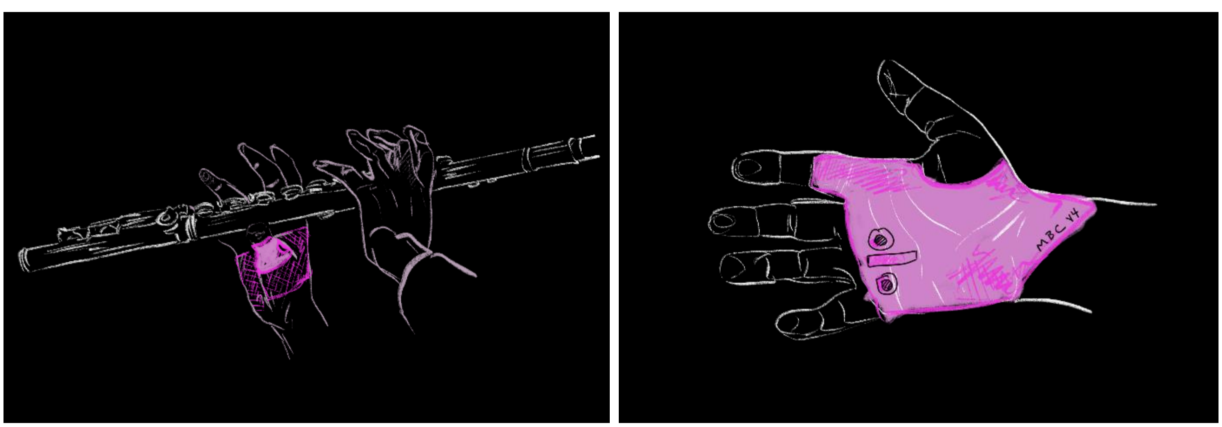


Fig. 2 MBC Drawings of Hand Concept, Fall 2020

Functioning Code

While there are several approaches to Bluetooth connectivity, one of the more basic, streamlined approaches is to treat the device like a reduced keyboard. By transmitting keycodes, the device mimics "arrows" back and forth between pages. Any ASCII keyboard may be applied to a push button. Breadboards and jumper wires connect an Adafruit Feather nRF52 Bluefruit LE in Fig. 3. Also pictured is a set of components ordered after code proofing.

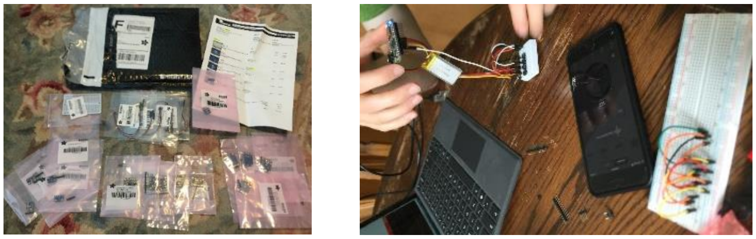


Fig. 3 Initial Prototyping with Working Code

The First Production

The first realization of MBC, "Build 02", came in a spurt of excitement. As seen in Fig. 4, the wires were soldered on with their joints still attached, and electrical tape secured push buttons to cardboard on top of a compression glove whose three fingers had been hacked off. An embroidery needle and thread were used to attach the Feather to the knuckle edge of the glove, and a 3.7V 500mAh Rechargeable Lithium Polymer ion (LiPoly) Battery Pack with a JST Connector sits behind the cardboard where the Feather rests.

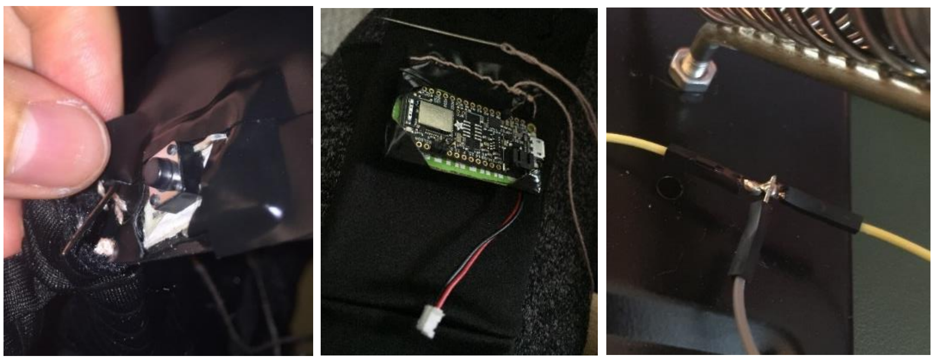


Fig. 4 Build 01 Insight Shots

In Fig. 5, more shots of the stitching and powering of Build 02 can be seen, emphasizing the double-finger structural design of the compression glove. The location of the "back" button behind the ring finger is a notable design choice that does not survive to the next build.

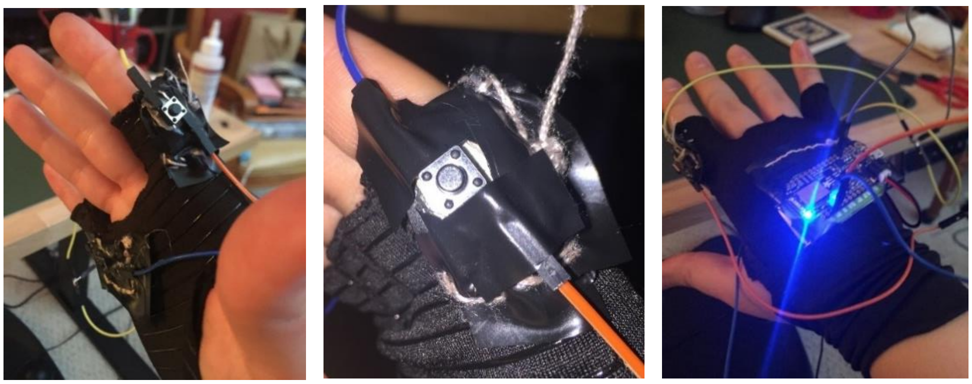


Fig. 5 Build 02 Production Shots

The Third Iteration

The Third Iteration of MBC can be seen in two builds, "3.1" and "3.2", that only adjust small structural aspects; this iteration introduces two new sensors for programmable functionality: a Micro-Electro-Mechanical (MEMS) microphone and an Inertial Measurement Unit (IMU) to capture tilt and acceleration.

The 3.1 Build

The most deliberate of the designs, Build 3.1 stretched over two full days of work and was largely made possible by the work of Kristi Best (KB) and Eli Best (EB). KB measured, designed, and executed all stitching, housing, and material integrity of MBC, particularly clever in the design on the wrist pocket to hold the LiPoly battery, Feather, and two slabs of foam to surround the battery and protect from abrasion and heat. She integrated hook-and-loop for adjusting tightness of the wrist on the user, as well as reinforcing the edges of the full model and repeatedly adjusting the location of the button pocket per the whims of the author of this report.

Fig. 6 Compression Glove Cuts of Build 3.1

EB orchestrated the wristband design to eliminate the tug of a straight component against the roundness of the top of the wrist. He also soldered all components lead wires and female headers, cut the compression glove to size, and modeled the glove pictured in Fig. 6. Also, as seen in Fig. 6, the new cut for Build 03 shows a single-finger design, as well as a cut-out on the side of the palm. This increases breathability of the glove for nervous musicians with sweaty hands, and it also allows for production to occur on both right-hand and left-hand gloves. Fig. 7 depicts the stitching, measuring, clipping, and eventual realization of Build 3.1.

Fig. 7 Stitching Construction of Build 3.1

The final product of Build 3.1 can be seen in the collection of images in Appendix A. Note that the testing wires protruding from the headers on the Feather create a gangly, high-strung set of connections from the sensors to the main board. While the eyesore is alleviated in Build 3.2, it was necessary for testing.

The 3.2 Build

The latest construction of MBC is a visual adjustment from Build 3.1, carrying over all hardware, code, and baseline design. EB and Kelly Weinzapfel (KW) heavily supported the fabrication. Fig. 8 shows the soldering and break work done by EB to join the components with the Feather without the protrusion of the test headers from Build 3.1. Pictured is the back of the push buttons that are housed on the index finger of the glove. To break the green breadboard, the board was placed between two sewing desks and forcibly pushed with great speed.

Fig. 8 Grunt Work Behind Build 3.2

While EB supported soldering, reshaping, and wiring, KW stitched the latest compression glove host of MBC. She utilized green thread to line the cuts along the glove, removing four of the five fingers and cutting off a piece of the thumb joint to use to secure the push button board firmly to the index finger. She also secured a hook-and-loop piece just along the knuckles, echoing the design of Build 01 and spanning the width of the hand. This hook-and-loop design choice was made during the completion of Build 3.1 to minimize the complexity of future builds and eliminate the dependency of the wrist in the final design, as this is a cumbersome structure for removal of the device. Thicker wires were used in Build 3.2, and these were wrapped in heat shrink to group the wires and merge the green styling of the thread and packaging to the glove, creating a more cohesive structure to the full unit. This is best seen in Appendix E.

While still incredibly bulky, the Feather rests on the top of the hand for Build 3.2. It is attached to the LiPoly battery by cuts of hook-and-loop, making it removeable and adjustable. Two hook-and-loop pieces sandwich the battery, and its JST connector hangs out to the side.

The on-off switch was devised from the Ruiz Brothers' guide on Adafruit's official website [8]. By connecting a mechanical switch between the negative lead to a female header for the JST battery, the user can now create an open circuit by flipping the switch. This alleviates the annoyance of manually unplugging the LiPoly battery for energy conservation.

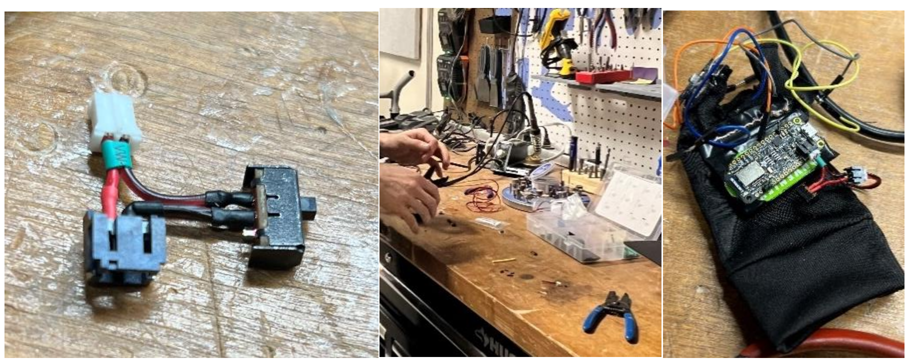


Fig. 9 Final Shots of Build 3.2, ft. a Power Switch

All three components are housed comfortably on the hook-and-loop patch on the back of the hand. Fig. 9 illustrates the incorporation of a hand-soldered On-Off switch so that the LiPoly can remain plugged in. It also shows all three units powered on and connected to the main Feather, completing the proof of concept.

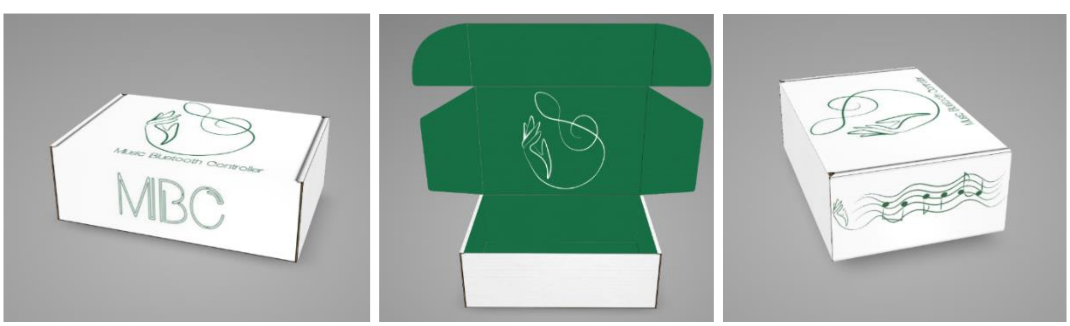


Fig. 10 The Packaging of MBC

Results

The latest iteration of MBC sports a fully functional page-turner on the index finger, as seen in Fig. 11 modeled on KW, as well as integrating hardware for future data analysis. The device is fully operational for its foundational purpose, utilizing Bluetooth and a wireless, rechargeable battery, making it simple and effective for performance and practice use.

Fig. 11 A Side-View of MBC Build 3.2

The design has been proofed on woodwinds, brass instruments, piano, and guitar, with feedback on button location, wiring, and glove cut. This directly impacted the location of the "Back" button, shifting it from the palm to the index finger to sit right below the "Forward" button. Feedback also influenced the finger design from two-finger based to one-finger based. These tests have demonstrated the utility of MBC, as well as the versatility cross-sectionally in an ensemble. See Appendix B for more images of playtesting with instrumentalists.

The final builds, side-by-side, show the shift in priority from build to build. The first build highlights proof of concept from the buttons, the second build focuses on intentionality of design, and the third build focuses on fluency of the wiring. See Appendix C.

Discussion

While the creation process was recorded in the Method section, the technical details of the code and materials used was not annotated directly. These components were discovered over the course of almost 3.5 years, and the final selection was sourced from Amazon, Adafruit, and Arduino, though the credit hardly stops with those juggernauts.

Software

The source code for the Feather was partitioned into three production pushes and roughly twenty staging builds. Keycode sources came from Arduino's Bluefruit52Lib, as well as Bluetooth connectivity (to replicate this project, reference the BLUEFRUIT.h and BLEHidGeneric.h header files). The keycode algorithm poles for any signal on specified pin inputs (MBC's program assigned 27 and 30) before launching Bluetooth signals of keycodes (MBC's case had "leftArrow" and "rightArrow") to a connected client. This was launched through an IF-statement with blehid.keyRelease(). A serial display can confirm the connection of the IMU and microphone sensors to the Feather, though this code is currently under-developed. At the time of publication, no Node-Red or other data visualization component has substantially materialized from the data collected by these sensors.

Hardware

While not the original board of choice for MBC's development, the Adafruit Feather has continued from Build 01 to Build 3.2 for its flexibility, versatility, and size. At a hefty price tag of about $26, the board isn't scalable, nor should it be: it was chosen for easy programming, testing, and proof of concept. The Silicon MEMS microphone (SPW2430) was also not the ideal component; at about $4.95 a board, it is inferior to an I2S MEMS breakout, both in programming and in data value, but the Feather is not compatible with an I2S—further incentive to shift away from the Feather and to a custom board, perhaps one on a PCB with a built-in microphone. The basic push buttons can be improved with silicon sleeves and padding, and the MPU-6050 6-Degrees of Freedom IMU has calibration demands that can be simplified on a custom board.

The compression glove incorporation was inspired by side-hand drawing gloves that sketching artists use to avoid smudging, but this was ultimately revised to lend the glove material to the left side of the hand rather than the right side because of thumb reach. Stitching used to hold the glove together varied in thickness, color, and origin, but had no significant design impact on the model. The on-off switch was originally going to be software-based to eliminate the need for further purchases, but a straight-forward tutorial [8] of a hardware switch on a JST connector from Adafruit guided the installation of a physical switch that cuts power from the LiPoly battery to the Feather without manually unplugging the battery. Heat-shrink surrounded the soldered switch connections to protect the wire from bending due to repeated interaction.

A Growing Team

MBC is a labor of love, motivated by a musician and her iPad, imagined by two engineering students, and realized by a rotating team of designers and architects alike. While it is exciting to follow the journey of the device, it is also important to step back and acknowledge the twists of the process and the people who took great strides to realize this product. See Appendix F for details on contributions of team members.

Cost Analysis

In its latest iteration, MBC's Build 3.2 costs $51.004 in materials alone. This is comparable to most Bluetooth Pedals on the market today, and some are cheaper. At the time of this writing, one can buy a ground unit for $39.99. However, practicing musicians will more likely trust a name-brand, heavier unit. Musicians often seek tactile response, long battery, and stability of system to not move on the ground while still being lightweight enough to carry around between performances. The STOMP page turner from Coda Music Technologies© runs

$169.95, and the Donner Wireless Page Turner pedal goes for $59.99. Three pedals, the Moukey, Starfavor, and AirTurn Duo 200, run for $55.99, $65.99, and $109.00, respectively. Overall, the average cost for a Bluetooth Pedal ($69.32) exceeds the upfront cost of MBC's materials ($51.01), but only marginally. A table with these brands and their prices and table with a breakdown of MBC's materials list are in Appendix D.

The functionality of MBC will increase beyond the scope of these existing technologies (namely, in data analytics of performance metrics), but current functionality is comparable to the technologies listed in the cost comparison section of this thesis.

Implications

MBC has exciting potential to shift definitions of "normal" in the sphere of musicians. Thus, it is valuable to discuss both limitations and future vision for the device.

Limitations

MBC has limited efficiency in code-cleaning; artifacts of Bluefruit code remain within the scripting on the prototypes, and the gyroscope readings, microphone readings, and inputs are unscaled and unadjusted. Amateur artists completed the soldering without formal professional training, and a switched JST connector may have fried the board for the second build. The glove stitching for the first build was haphazardly done with a thick embroidery thread, and the push buttons can be swapped out for more durable capacitive sensors that can be programmed on the Feather itself. One custom PCB should eventually group the Feather and its branching sensors into a unit without the sticker tag of a name-brand chip. Limited expertise underpins the current hardware limitations. Time and funding constraints for proper board research and design are additional roadblocks.

Future Vision

The next stage of MBC will lean into the microphone, humidity, and IMU functionality of the glove. Node-RED will communicate data metrics gathered from these chips to inform the musician of his habits during a playing session: has he been bending his wrist forward too much? Has his pitch consistently sunk down into flat ranges? Has his hand perspired or shaken more than normal? Has his gesturing been more erratic than usual, or does it verge on “distracting”? Musicians will quantify these questions by watching the gyroscopic and accelerometric readings from the IMU, the humidity readings from the Feather, and the pitch readings from the microphone. A summary dashboard (either web-based or device-based) will display the data so that the musician and any stakeholders such as professors, adjudicators, or students can learn from the musician’s playing habits. Immediate plans for MBC are expanded in Appendix G.

References

[1] I. G. Lee, K. Go and J. H. Lee, "Battery Draining Attack and Defense against Power Saving Wireless LAN Devices," *MDPI Sensors*, vol. 20, no. 7, pp. 2043-2057, Apr. 2020, DOI: 10.3390/s20072043.

[2] J. Tosi, F. Taffoni, M. Santacatterina, R. Sannino and D. Formica, "Performance Evaluation of Bluetooth Low Energy: A Systematic Review," *MDPI Sensors*, vol. 17, no. 12, pp. 2898-2933, Dec. 2017, DOI: 10.3390/s17122898.

[3] M. M. Al-Kofahi, M. Y. Al-Shorman and O. M. Al-Kofahi, "Toward energy efficient microcontrollers and internet-of-things systems," *Computers and Electrical Engineering, v*ol. 79, pp. 106457-106468, Oct. 2019, DOI: 10.1016/j.compeleceng.2019.106457.

[4] T. T. Khanh, V. Nguyen, X.-Q. Pham and E.-N. Huh, "Wi-Fi Indoor Positioning and Navigation: a Cloudlet-Based Cloud Computing Approach," *Human-Centric Computing and Information Sciences,* vol. 10, no. 32, pp. 1-26, Jul. 2020, DOI: 10.1186/s13673-020-00236-8.

[5] S. Kim, M. Park, S. Lee and J. Kim, "Smart Home Forensics—Data Analysis of IoT Devices," *MDPI Electronics*, vol. 9, no. 8, pp. 1215-1228, Jul. 2020, DOI: 10.3390/electronics9081215.

[6] A. A. Zaidan and B. B. Zaidan, "A review on intelligent process for smart home applications based on IoT: coherent taxonomy, motivation, open challenges, and recommendations," *Artificial Intelligence Review,* vol. 53, pp. 141-165, Jul. 2018, DOI: 10.1007/s10462-018-9648-9.

[7] L. S. Lo, "Reciever Circuit with Low Power Consumption and Method for Reducing Power Consumption of Receiver System". United States Patent US 10,601,519 B2, 24 March 2020.

[8] R. Brothers, "DIY On/Off JST Switch Adapter," Adafruit, 22 March 2017. [Online]. Available: https://learn.adafruit.com/on-slash-off-switches. [Accessed 01 02 2022].

Additional References

I. C. Bertolotti and G. Manduchi, *Real-Time Embedded Systems: Open-Source Operating Systems Perspective*, Boca Raton, FL: Taylor & Francis Group, LLC, 2012.

P. P. Chu, *Embedded SoPC Design with NIOS II Processor and Verilog Examples,* Hoboken: John Wiley & Sons, Inc., 2012.

S. L. Harris and D. M. Harris, *Digital Design and Computer Architecture,* ARM Edition, Waltham, MA: Elsevier Inc., 2016.

B. J. LaMeres, *Introduction to Logic Circuits & Logic Design with Verilog*, Bozeman, MT: Springer International Publishing, 2017.

B. P. Lathi and R. Green, *Linear Systems and Signals*, 3rd Edition, New York, NY: Oxford University Press, 2018.

B. P. Lathi and Z. Ding, *Modern Digital and Analog Communication Systems*, International 4th Edition, New York, NY: Oxford University Press, Inc., 1983.

M. Mannino, *Database: Design, Application, Development, & Administration*, 7th Edition, Chicago, IL: Chicago Business Press, 2019.

R. K. Nagle, E. B. Saff and A. D. Snider, *Fundamentals of Differential Equations*, 9th Edition, Pearson.

M. Palmer, *Guide to UNIX Using Linux*, 4th Edition, Boston, MA: Cengage Learning, 2008.

L. L. Peterson and B. S. Davie, *Computer Networks, a Systems Approach*, 5th Edition, Burlington, MA: Elsevier, Inc., 2012.

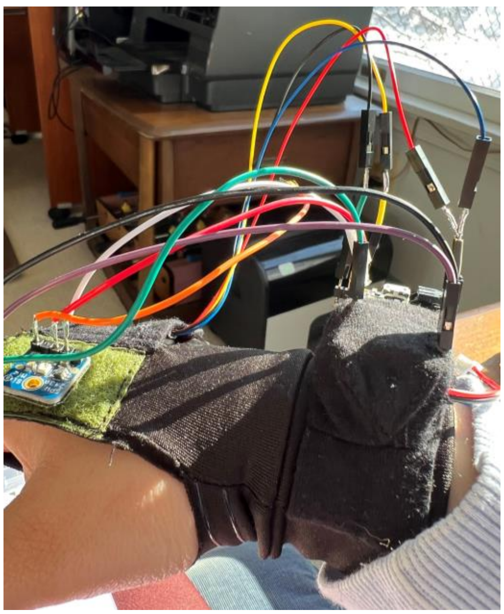
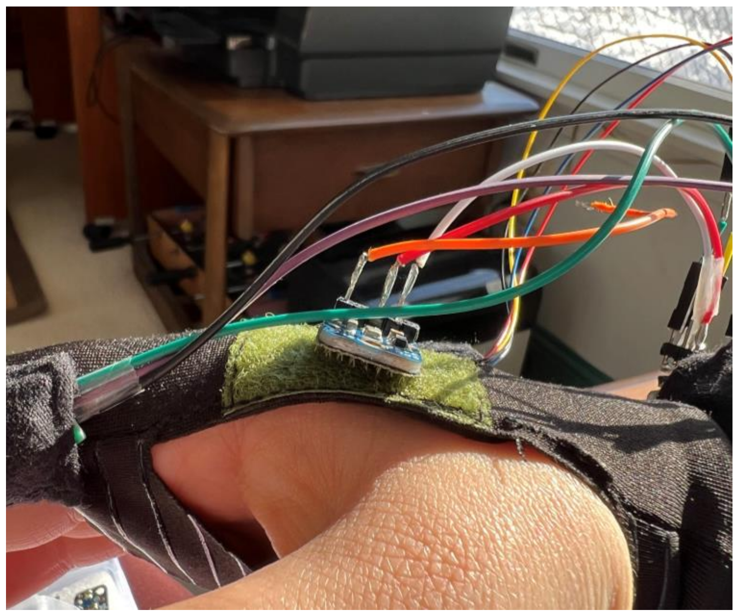
C. A. Schuler, *Electronics: Principles and Applications*, 9th Edition, New York, NY: McGraw-Hill Education, 2018.

J. W. Valvano, *Real-Time Operating Systems for ARM Cortex-M Microcontrollers*, Vol 3, 4th Edition, University of Texas, 2017.

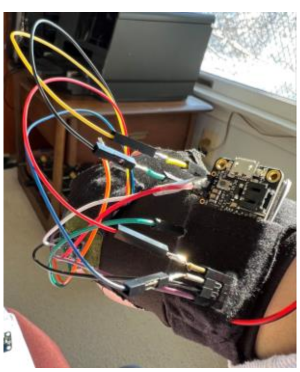
Appendix A

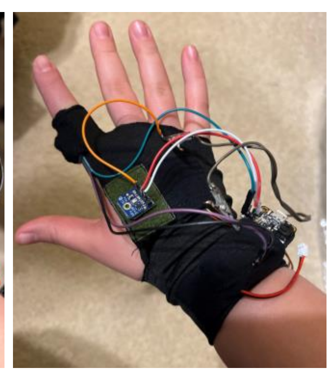
Build 2.1 Photos

The photographs below are a collection from the 2.1 build in Alexandria, Virginia. Kristi Best demonstrated skilled handiwork in the stitching of the green hook-and-loop padding and the wrist band pocket that houses a “circuit sandwich”: a layer of foam, the LiPoly battery, another layer of foam, and the Adafruit Feather.

Additionally, these images show the high-winding nature of the wires; the system is not contained, and jumper wires with female heads have been used for trouble-shooting and testing.



Appendix B

Playtesting of MBC

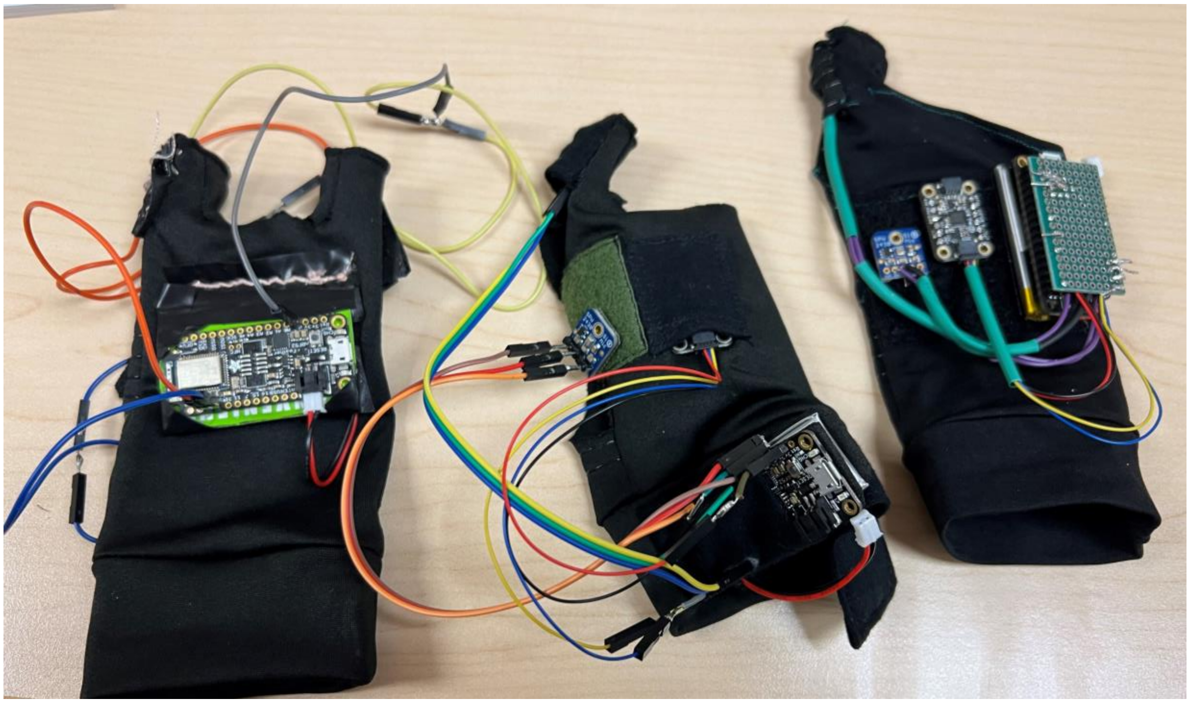
Play Testing MBC Build 01 Above, Play Testing MBC Build 03 Below

Appendix C

Three Models of MBC, Side-by-Side

The defining features of each of the iterations of MBC are clearer in the image of this Appendix, shown here from left to right in terms of build. The left-most image, Build 2.0, has two fingers. Its buttons are located along the index finger and along the palm. It has only the Feather and LiPoly battery, no additional sensors, and no on-off switch functionality. Finally, all wires are jumper wires to the main Feather board, and a cardboard cut-out and embroidery thread stitched through electrical tape hold the component to the glove.

The center image is a production prototype of Build 3.1. With a single finger, the additional sensors, utilization of hook-and-loop, and the adjustment of placement for the forward-backward buttons, this is a distinct model class from Build 2.0. Then, while there are aesthetic changes between the middle and right-hand models, the functional aspects these two models are identical, so the right-hand prototype is labeled “Build 3.2” instead of “Build 4.0”.



Appendix D

Cost of Production: Breakdown Table

The following tables hold a record of the purchase dates, quantities, origins, and locations of components obtained to support the eventual realization of MBC. Additionally, a Bill of Materials (BOM) table shows the baseline cost to build one Build 3.2 model of MBC. This log does not include time, labor, or shipping costs. Total expense for Build 3.1 alone is $304.85 for production.

Bill of Materials, MBC Build 3.2: One Model	
Component Name	**Cost**
Adafruit Feather nRF52 Bluefruit LE - nRF52832	$ 25.60
3.7V 500mAh 502248 Lipo Battery Rechargeable Lithium Polymer ion Battery Pack with JST Connector	$ 8.49
1 Copper Arthritis Glove Fingerless (S)	$ 3.215
STEMMA QT / Qwiic JST SH 4-pin to Premium Male Headers Cable - 150mm Long	$ 0.95
Adafruit MPU-6050 6-DoF Accel and Gyro Sensor - STEMMA QT Qwiic PID: 3886	$ 6.95
Adafruit Silicon MEMS Microphone Breakout - SPW2430 PID: 2716	$ 4.95
2 Pcs 6mm 2 Pin Momentary Tactile Tact Push Button Switch	$ 0.599
Kester Solder	$ 0.25
TOTAL Cost for Materials of 1 Unit	**$ 51.004**

In early Fall 2018, the team set the 4-year project budget at $500 ($125 dollars a year, including shipping, materials, consultation, construction, and manufacturing expense). This report does not account for any details of 3D-printing Build 1.0 (including costs) which was an instrument-centered design instead of a human-centered design. Also not accounted for in this report are the costs per hour of the consultation and team lead time in developing this product.

It is important to note that this cost is highly inflated due to the use of commercial, name brand components instead of off-brand devices. The breakout boards and the Feather board especially contributed to rising cost, coming to over half of the total component cost at a whopping $37.054). This would be easily halved, even quartered, by commissioning a custom PCB in a factory offshore, bringing the estimated production cost per unit closer to $32.031. While this claim does not explicitly consider the cost of engineering a scalable, modular circuit instead of hooking together pre-existing hardware as we now have with Build 3.2, limiting excess components and features would come out better in a mass-production setting.

Bill of Materials, MBC Build 3.1				
Purchase Date	**Name**	**Qty.**	**Cost Per Item**	**Total Cost**
6/15/2021	Adafruit Feather nRF52 Bluefruit LE - nRF52832	5	$ 25.60	$ 128.00
6/15/2021	6 Pieces Artist Glove for Drawing Tablet (S M L), Gzingen Two-Finger Tablet Drawing Gloves, Digital Artist Gloves for Graphics Pen Drawing Tablet Monitor Light Box Tracing Board-Three Size in One	1	$ 8.99	$ 8.99
6/15/2021	3.7V 500mAh 502248 Lipo Battery Rechargeable Lithium Polymer ion Battery Pack with JST Connector	5	$ 8.49	$ 42.45
6/19/2021	Duerer Arthritis Compression Gloves for Women and Men (Black, Small)	1	$ 8.99	$ 8.99
6/19/2021	Copper Arthritis Gloves, Fingerless Compression Hand Gloves (S)	1	$ 6.43	$ 6.43
6/19/2021	Tikaton Arthritis Gloves Compression Gloves (Black, Small)	1	$ 8.99	$ 8.99
7/17/2021	Adafruit I2S MEMS Microphone Breakout - SPH0645LM4H PID: 3421	4	$ 6.95	$ 27.80
7/17/2021	STEMMA QT / Qwiic JST SH 4-pin to Premium Male Headers Cable - 150mm Long PID: 4209	5	$ 0.95	$ 4.75
7/17/2021	Adafruit MPU-6050 6-DoF Accel and Gyro Sensor - STEMMA QT Qwiic PID: 3886	5	$ 6.95	$ 34.75
7/17/2021	Adafruit Silicon MEMS Microphone Breakout - SPW2430 PID: 2716	2	$ 4.95	$ 9.90
7/17/2021	Standalone Momentary Capacitive Touch Sensor Breakout - AT42QT1010 PID: 1374	4	$ 5.95	$ 23.80
1/4/2022	20 Pcs 6mm 2 Pin Momentary Tactile Tact Push Button Switch	1	$ 5.99	$ 5.99

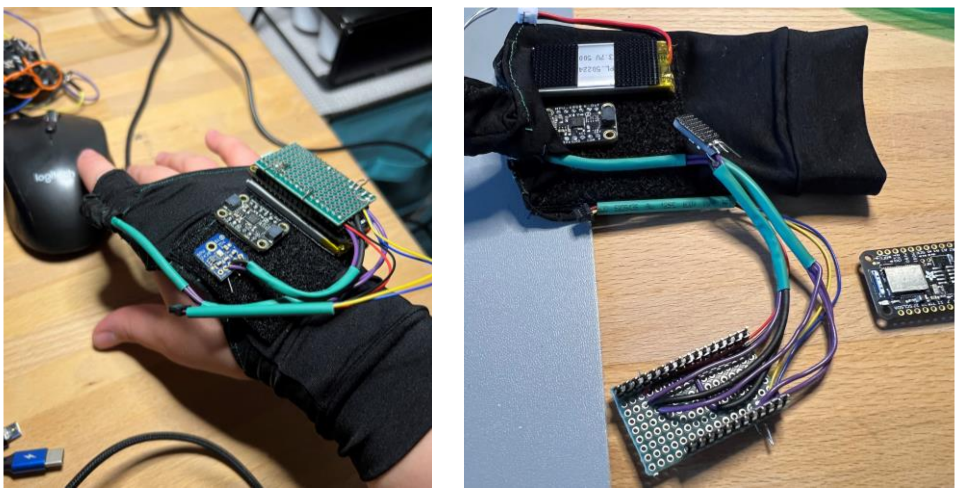
The table below lists current page turner technologies for performing musicians. These are the top fifteen results found by searching “Bluetooth Page Turner” on Amazon on March 21st, 2022. The average cost from this sampling of comparable units (functionally) is $69.32, above MBC’s upfront materials cost.

Index	**Name**	**Brand**	**Cost**
01	Smart Wireless Page Turner Pedal	Lizhoumil	$22.99
02	Cube Turner	Fesjoy	$25.69
03	Music Page Turner for Tablets	Playwell	$27.99
04	Wireless Foot Pedal Double Switch	Yueyinpu	$39.99
05	Wireless Sheet Music Page Turner	Aikongcd	$39.99
06	Bluetooth Page Turner	Lekato	$50.39
07	Wireless Page Turner Pedal	Moukey	$55.99
08	DBM-1 Wireless Page Turner Pedal	Donner	$55.99
09	Wireless Page Turner Pedal	Donner	$65.99
10	Silent Page Turner Pedal	Starfavor	$65.99
11	Butterfly Bluetooth Page Turner Pedal	PageFlip	$89.95
12	Butterfly Bluetooth Page Turner	PageFlip	$89.95
13	Duo 200 Silent Bluetooth Pedal	AirTurn	$109.00
14	Dragonfly Bluetooth Pedal	PageFlip	$129.95
15	Bluetooth 4.0 Page Turner	STOMP	$169.95

Appendix E

Behind-the-Scenes Construction of Build 3.2

Soldering, Stitching, and Hook-and-Looping of Build 3.2



Approaching Full Construction of Build 3.2

K. Weinzapfel was instrumental in the completion of the glove base for MBC Build 3.2. The decision to go with a single hook-and-loop square instead of the more isolated, deliberate patches from Build 3.1. was motivated by convenient installation. See the select patches attached via adhesive on the back of the Adafruit Feather for ease of attachment to the back of the glove without damaging the hardware.

L. Wu grouped the wires via heat shrink tubing, matching the aquamarine threading color that accents the glove. E. Best designed and soldered the grouped wires directly to an aquamarine perf board to attach to two rows of male headers soldered to the Feather.

Appendix F

The Team Supporting MBC

MBC Team, Left-to-Right: Lydia Wu (Co-Founder, Author), Eli Best (Co-Founder), Kelly Weinzapfel (Artistic Consultant), Dr. Feng Wang (Device Consultant), Kristi Best (Materials Consultant)

Ignorance can easily overwhelm excitement. While the visions of MBC's scope grew without restraint, the magnitude of MBC's technical requirements often overwhelmed the joy of brainstorming its future. Freshmen Lydia Wu (B.S. Computer Engineering) and Eli Best (B.S. Mechanical Engineering, B.S. Mathematics) had little experience developing IoT devices, utilizing Bluetooth, or communicating with professionals, both academic and industrial. This created hiccups in building MBC, resulting in long stretches of inactivity filled with other coursework. As Wu and Best progressed in their academic careers, they accrued coursework in embedded systems, communications, C++, SolidWorks, Technical Communication, and design knowledge on how to approach MBC. Undergraduate enrollment has fostered a mindset of reaching out for help, and MBC became a group effort as Kelly Weinzapfel (B.S. Studio Arts), Kristi Best (B.S. Mathematics Education), and Rachel Pruski (B.S. Strategic Communications) contributed non-technical support in the design, construction, and marketing of the product. Finally, Dr. Feng Wang and Dr. Young-Man Kim edited and advised both technical and meta-technical aspects of the various builds of MBC.

Appendix G

Close-By Future Plans

MBC has been a featured project in a high-school recruitment tour with Liberty University's Dean of Engineering in Spring 2022 to demonstrate potential real-world applications in interdisciplinary fields of engineering. Liberty University's Research Week 2022 featured MBC in two separate events: the Oral Presentation, and the Three-Minute Thesis. It is also projected to be featured in an IEEE Spectrum article to be published by the end of 2022, advised by Dr. Wang. Before this publication, the team will build MBC 3.3, constructed off a new version of the Adafruit Feather and featuring a modified glove design for easier removal of MBC. A three-button membrane switch will be utilized instead of the tactile push buttons of Build 3.2, and the hook-and-loop patch will not have an adhesive, alleviating the issue of mucked needles from machine sewing. This build has a BOM just shy of $300 for development, and the construction will result in at least one department-owned, fully functional device.

Following MBC's software-heavy development in data analytics, the device will undergo another hardware shift: a custom PCB with the components, leaning away from the name brand plug-and-play nature of the Feather, and a soft, flexible silicon housing to prevent tampering and damage. The compression glove will feature more cut-outs for easier breathing, and the glove will have a user-friendly hook-and-loop closure to facilitate removal from the hand. Backhand fabric real estate and the wrist of the glove will disappear. MBC will see a shift from tactile breadboard buttons to capacitive sensors to reduce bulk, flattening the touch point but still allowing for mechanical response. MBC will continue to develop, hopefully growing into an indispensable aid to the modern flutist.