Embedding Electronics in Additive Manufacturing for Digital Musical Instrument Design

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ABSTRACT

The fast-growing technology of additive manufacturing-(AM), 3D printing, enables unique features in numerous design areas including musical instrument design. The recent advancements further introduce incorporating electronics into 3D printing. While still in the proof of concept phase, the ability to fabricate embedded sensors with 3D printing offers promising applications for musical instrument design.

In this paper, embedding sensors and functional parts in the additive manufacturing process is discussed. We present the design process of embedded sensing for rapid prototyping digital musical instruments (DMI). The establishment of 3D models and operation sequences for different musical applications can be challenging since they vary depending on the electronic components. In order to address this problem, we provide a set of design and manufacturing specifications to customize the prototyping process for embedding structural electronics. The application of this hybrid method is demonstrated with two case studies: modular structures for a wearable gestural controller and an augmented flute. These instruments present the current stage of the technology which uses fused-deposition modeling (FDM) and the advantages and challenges of hybrid AM in musical instrument design as well as its future directions.

1. INTRODUCTION

Electronic components including sensors, controllers, etc. constitute one of the primary means of interaction in computer music [1]. Marshall and Wanderley show that the majority of digital musical instruments' sensing mechanism includes certain commonly used sensors such as accelerometers, touch or force sensitive sensors, and proximity sensors. From manufacturing point of view, prototyping with these electronic components hardly exceed printed circuit board (PCB) technology in digital musical instrument (DMI) design except for few examples [2]. For example, Wicaksono and Paradiso's stretchable keyboard demonstrates interaction methods with textile sensing in their "deformable musical interface" [3]. This design shows the potentials of adopting newer tactile sensing mechanisms into our current use of DMI prototyping techniques [4,5]. Examples of both conductive textile and PCB applications in interaction design also demonstrate promising implementation areas of 3D printing electronics [6,7].

Rapid prototyping using 3D printing tools attracts music instrument designers to manufacture new or cheaper forms of musical instruments. These efforts mainly focus on replicating existing acoustical instruments—mainly violins, flutes, and guitars—as well as leveraging the flexibility of computer-mediated design and manufacturing to create new forms of instrument parts such as valves, mouthpieces, or unconventional tonal series. Similarly, AM tools are used to print instrument enclosing, augmentation parts, prosthetic instruments, etc. [2].

Although designers leverage the affordability and the availability of AM tools for prototyping or creating new instruments, they frequently incorporate electronics independently from 3D printing for various purposes, ranging from embedded musical instruments to wearable and bio-sensing musical interfaces. There has not been an example combining digital sensors with rapid manufacturing techniques in the same process for musical applications so far, to the extent of our knowledge. Incorporating electronics into AM processes can improve not only the form and appearance of final products, but also functionality of the digital elements in DMIs. This paper introduces the musical implementations of embedded sensing by integrating sensors and/or passive components in 3D printed designs. It discusses how to implement this hybrid method using fused deposition modelling (FDM), a widely used 3D printing process, and demonstrates how hybrid AM can be used for creating new musical interfaces.

This paper is structured as follows. Section 2 provides background information about the recent approaches to embedded electronics in AM. Section 3 discusses implementation of hybrid AM using FDM printers. Section 4 describes design methodologies and demonstrates creating musical instruments with embedded sensing by demonstrating two case studies. Section 5 further explains the modular design approach to music instrument design that could benefit embedded sensing approach and discusses the continuation of this work.

2. BACKGROUND

Additive manufacturing techniques are integrated into design, creation, and prototyping practices of artists, musicians, and DMI designers. Due to its cost-effectiveness, availability, and affordability for customization, this manufacturing method is adopted into music research and education [2]. However, its use in music applications stays behind the recent advancements that are more frequently explored in other fields. The combination of electronic components with 3D printed structures in a single manufacturing process has not yet been employed to designing, prototyping, and manufacturing DMIs. In this section, we find it valuable to briefly introduce some of the current technologies for embedded sensors as well as the existing applications of additive manufacturing and electronics uses for digital musical instruments.

2.1 Embedding Electronic Components in 3D Printing

Dijkshoorn et al. describe three recent methods for embedding sensors: hybrid approaches, conductor infusion, and multi-material printing [8, 9]. Hybrid approaches, or multiprocess printing, include combining non-AM fabricated structures such as wiring, circuit boards, or the entire sensors. Macdonald et al. explore this 3D printing method for printing structural electronics and develop an embedding approach called stop-and-go approach [10–12].

Macdonald leverage the flexibility of fabrication with 3D printing to create more appropriate shapes of the electronic devices than their 2D bread-boarded counterparts. They explain how 3D printed electronics reduce the duration of products' development and prototyping cycle, avoid the subtractive manufacturing process to carve the wiring channels, and allow designers to create more complicated and compact shapes than 2D layer breadboard or printed circuit board (PCB) configurations [10]. Besides the advantages of this method, they also discuss the drawbacks of their current printing methods (stereolithography (SL) fabrication, depositing conductive ink, etc.) and offer alternative methods (FDM or material extrusion fabrication, inkjetting, embedding solid wires, etc.). As the authors emphasize, the current improvements—in more easily accessible 3D printers such as Ultimaker, Makerbot, and equivalents—such as dual extrusion, multi-material printing, and conductive or magnetic material extrusion enable designers to prototype the functional electronics structures in a single process. Additionally, these features allow them to skip the subtractive processes as Lopes et al. and Arnold et al. adopt in their hybrid manufacturing system [12, 13].

Another common method for embedding sensors is conductor infusion method, an AM method that prints wiring channels using a soluble support material. These channels are later filled using conductive ink infusion [8]. Although this method is advantageous for creating complex electrical wiring thanks to their independent formation from the main fabrication method, dissolving the support material, as well as the actual infusion process itself, imposes several challenges. The infusion process significantly varies depending on the suspension method, conductive material's properties, and the geometry of the wiring. On the other hand, multi-material printing appears as the most advantageous and convenient type of printing among the current technology. This method combines conductive and nonconductive materials in the same print cycle [8]. Leigh et al. demonstrate printing flexible electronic sensors to sense mechanical flexing and capacitive touch. With their material, they prototype flex sensors—printed on flexible strips and embedded in an exo-glove—and capacitive buttons – printed on a 3D printed board as a capacitive interface device and embedded in a vessel to detect the water level.

2.2 3D Printing and Electronics in DMI Prototyping

Contrary to the recent advancements in the rapid prototyping area, the majority of examples in musical instruments that explore additive manufacturing methods put little emphasis on hybrid manufacturing or incorporating electronics [2]. An example of research that focuses on design and manufacturing DMIs include uses of 3D printing and laser cutting for prosthetic instruments designed by Hattwick, Malloch, and Wanderley [14]. The electronics used in these instruments include magnetic wiring, PCB, and conductive pads which are assembled in the final prototyping stage. Later, Kalo and Essl fabricated a cymbal using robotic sheet forming method [15]. While this work does not include any electronics manufacturing or prototyping process, it presents an example of a novel personal fabrication technique adopted to music research. In her survey, Cavdir discusses Wessel's Slabs as an earlier example for piezoresistive sensing [16] and how Wessel's prediction about the printable electronics with Inkjet technology for DMI design translates to the recent technology of fabricating flexible tactile sensors using 3D printing [2, 6, 7, 17].

Although the electronics printing has not been integrated into DMI prototyping, the use of digital sensor technology in musical interfaces predominates these processes. To overview the applicable areas of this research, surveying the most commonly used sensors becomes crucial. Marshall and Wanderley present an extensive review on the existing computer music interfaces and the sensors/electronics technology used in these sensors [1]. Authors report that the most commonly used sensors include accelerometer, force sensitive resistor (FSR) and proximity sensing followed by capacitive touch and bend/flex sensors.

In addition to the sensors used in physical interface design, with the increasing trend in movement and gesture detection based interfaces, the use wearable and flexible sensors has been rapidly growing. These sensors mainly include accelerometers, gyros, inertial measurement units (IMUs), bio sensors—EMG, EKG, EEG, microphones and breath sensors—, and stretchable capacitive sensors. With the focus on the types of sensing mechanism and wearability of the interfaces, integrating the electronic parts into the rapid prototyping/manufacturing significantly increases the speed of this process. Embedding these functional elements allows for more compact, sturdy, and comfortable interfaces for augmenting instruments, designing wearable devices, and in general new DMIs.

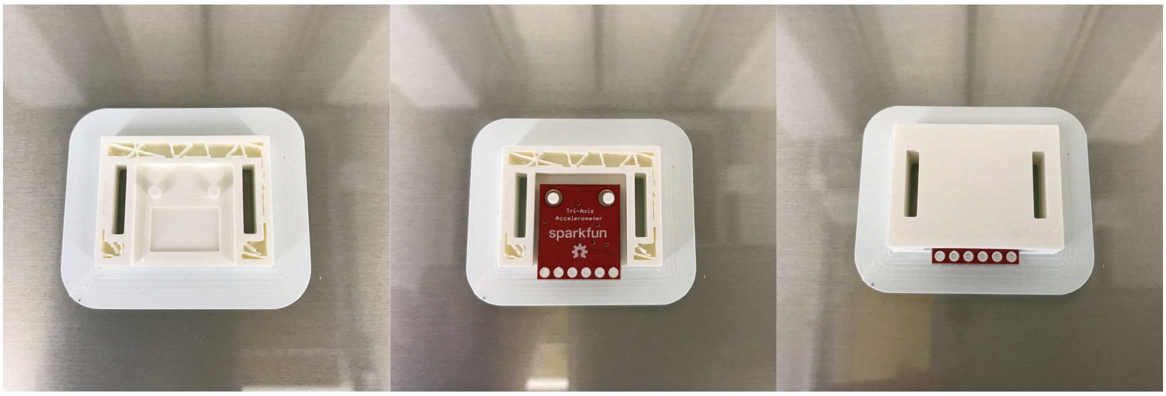
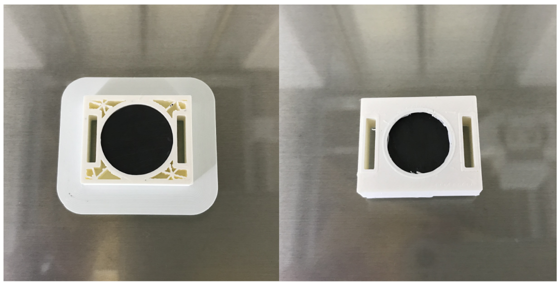


Figure 1: Embedded accelerometer is manufactured using hybrid AM method. The first image (i) shows the model right after pausing, the middle image (ii) shows the accelerometer placed for embedding, and the last image (iii) shows the finished part with the sensor enclosed. The pin-out is left exposed for easy connection and not intruding the nozzle's movement with the external objects such as cables, excessive solder, or connectors

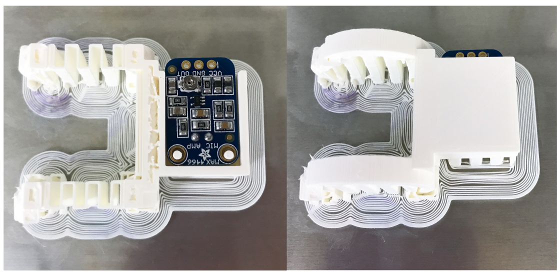
3. EMBEDDING ELECTRONICS IN AM

In this work, we embed two electronics components, an accelerometer and a microphone with an amplifier breakout, and a passive component, a magnet, (see Figures 1, 2b, and 2a) with multi-process approach using Ultimaker 3 Extended 3D printer [18]. This approach requires modifications in creating 3D models and slicing those models for G-code generation. The main modification needed in the embedding process is pausing the print at the right time and location. Although the pausing process can be done manually using the printer's control panel, this process provides better results when the pause command is handled by modifying the G-code. Modification in the code is advantageous over manual interruption for two reasons: 1) the correct layer, which could be more than one layer in one process, is difficult to predict by inspection and 2) the printer hardly guarantees that it saves the location of the print head where the process is paused. The latter varies with the type of 3D printers. The printer we tested this approach, Ultimaker 3 Extended, remembers the last print state; however, it is not always possible to manually pause the print exactly at the intended location and time. On the other hand, modifying the G-code provides full control over the print process including selecting the right layer, modifying and recovering the print head height, and monitoring the expected time of the stops.

Figure 3 shows the necessary modifications in the G-code for pausing the print job to embed the piece. Since this modification varies with 3D printer's specifications, main consideration in this process becomes whether the printer can recover the print head's location back to the position where it is paused. Although newer versions of some 3D printers remember the current state of the print head and are able to return to the last x, y, and z axes positions when the print job is resumed, some printers require explicit control of the print head's positioning. Since the 3D printer used in this research saves the correct position of the print head where the print job is stopped regardless of the pausing method—either through G-code or using printer's control panel—and it returns to that position when resumed, our process did not require additional G-code change apart from inserting the pause command at the right layer. Figure 3 shows pause command added to the code after slicing the 3D model for those 3D printers that have the capabilities to save and return to the right position. This feature



(a) Embedded magnet is worn multiple location to capture the finger gestures with the hall effect sensors.



(b) Embedded microphone is attached to the mouthpiece of the alto flute.

Figure 2: 3D models are designed to embed the sensors into the printed parts without interfering with the printer's nozzle motion. (2a) offers a flat surface that is easy to embed while the microphone amplifier breakout in (2b) needs to be embedded in a position that both allows for placing the microphone facing the build plate as well as leaving room for nozzle to move freely without touching the sensor.

```
...
G1 F1500 E336.86611
;MESH:NONMESH
G0 F600 X107.635 Y114.65 Z4.97
...
;TIME_ELAPSED:2284.677739
;LAYER:47
M204 S1000
M205 X10 Y10
;TYPE:WALL-INNER
;MESH:version0.4.STL
;First Stop
M25 ; Pause the print
G1 F1000 Z40 ;Raise to Z = 40
G1 F1500 E343.36611
G1 F1800 X122 Y108.678 E343.36643
G1 X122.02 Y108.746 E343.36677
G1 X122.016 Y108.819 E343.36711
...
M204 S5000
M205 X30 Y30
G1 F1000 Z4.97
;Return after the first non-G1 command
...
```

Figure 3: Pause command inserted after slicing the part and generating the G-code for 3D printers. For printer that does not require recovering the nozzle height position, only the pause comment, M25, is sufficient. Raising and recovering the nozzle height position is codded in addition to the pause command.

helps simplifying the code modification process by avoiding additional coding for raising the extruder and returning to the correct Z height. However, some other FDM printers do not offer this feature. In this case, manipulating the height (z location) of the print head is required. Figure 3 shows the G-code needed for such type of pausing process.

The codes for the print head control can be found in NIST RS274NGC G-code standard publication [19]. The lines starting with G0 and G1—move commands—with x, y, z axes data indicates the coordinates of the nozzle while E343 is used for how much material needs to be extruded. M25—"pause print from a SD card" command—is used for pausing the print process at the desired height (see Figure 3, below "First stop" command). M226—"G-code initiated pause" command—can also be used for initiating a pause in the same way as if the pause button is pressed.

The height where the print processes needed to be paused can be monitored by inspecting either the layer number indicated in the automatically generated slicer comments, the z position of the extruder from an earlier layer, or by the time elapsed. The most reliable method for finding the correct pausing layer is by calculating the exact z axis indicated in the G-code at the end of each layer. The correct height for embedding sensors based on the original CAD design comparatively matches with z axis information from the G-code since the slicing software introduces some variation when breaking the model into distinct layer increments. These increments vary with layer height predetermined in the settings of the slicing software based on the print quality (normal, fine, extra fine, etc.). The printer and its associated software in this work allows decreasing the layer height up to 0.06 mm when the profile is set to extra fine. This layer thickness is fine enough to discard variation in choosing the right z axis. The parts in Figure 1 and 2a are printed using the "fine" settings with layer height of 0.1 mm.

After successful embedding, the print process can be resumed from the LED display. Similarly, the resume process can be adjusted by G-code. Our print tests did not necessitate this process since we were able to get the same accuracy and control unlike in the pausing process.

Most recent versions of some slicers allow for inserting certain G-code commands, including pausing and changing material types at certain z axis positions as part of the slicing process. The slicer used in this work offers this feature through plugins to insert code into the already sliced files. Our experience with this type of post processing hardy showed consistency in modifying G-code when inserted in the slicer software compared to more successful and flexible modification when manually programmed into the code.

In addition to controlling the pause and return specifications, another major consideration comes from the temperature sensitivity of the electronic equipment and the heating range of the printer. Because some sensors show more temperature sensitivity, extruding hot material directly onto the electronics part or placing them in contact with the hot build plate might disturb the calibration and/or proper functioning of the sensors. The extruder and bed temperatures can be set by modifying the code again. In the prototypes we presented here, we designed the models to avoid direct contact of electronics with hot material and allow enough cooling time for the already printed parts during embedding.

In the module in Figure 1, the accelerometer (ADXL335) can compensate the temperature limits between -55 and 125 °C when powered, -65 and 150 °C when in storage [20]. Similarly, the microphone breakout can operate at the temperatures between -40 and 85 °C and can be stored between -65 and 150 °C [21]. Since the print bed is heated up to 60 °C [18] and material cools down sufficiently fast, embedding the electronic component after a short wait and leaving 1-2 layer distance between the first layer after embedding are tolerable for safe printing processes. Both electronic components are tested before and after the embedding process and did not show any difference in their operation.

4. DESIGN APPROACH AND APPLICATIONS

4.1 Gestural Controllers

The embedded sensors allow for compact, attachable, and tangible interaction modules which are crucial in designing wearable interfaces. Figures 1 and 2a show the embedded accelerometer and magnet modules designed for a wearable gestural controller, *Felt Sound* (see Figure 4).

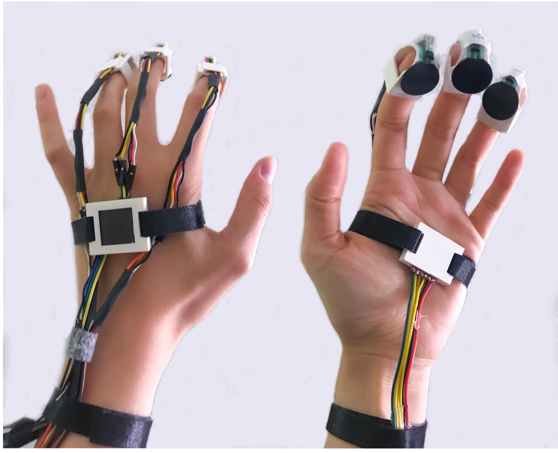


Figure 4: Felt Sound interface captures hand and finger gestures. The wearable parts are designed by embedding magnet and accelerometers during the print process.

The embedding method allowed us to design the sensors in a compact way to capture finger and hand gestures. The interface captures few selected American Sign Language (ASL) gestures and maps them to the control of the sound engines [22].

In *Felt Sound*'s design, we adopted the modular design approach to offer designers more flexible methods for creating gestural interactions since the modules can be combined in multiple ways to capture several gestures using the same detection mechanisms [23–25]. This interface requires the musician to perform with sign language gestures with a limited set of sensing mechanisms: FSR and hall effect sensor modules, accelerometer (inside the palm), and magnet (outside the palm) modules. Because of the limitation in the number of sensors, modular design allows the performer to relocate the modules in multiple locations on hands and wrists to capture different gestures.

In *Felt Sound*, the overall interface required embedding active (FSR, hall effect sensor, accelerometer) as well as passive (magnet, attachment pieces) elements within the modules. The flexibility of combining these elements enabled us to distribute the individual modules into different fingers, left or right hand, wrists, and arms. For example, placing the magnet module on the same hand with hall effect sensors allows the musician to capture finger gestures whereas distributing these two modules can extend the interaction between two hands. The same mechanism can be applied to detecting fingers' opening and closing gestures when finger sensor modules are worn on the same hand. For example, the accelerometer is placed inside the palm to capture the hand's wobble and waving gestures. The accelerometer module can also be placed on the wrist or arm for larger-scale arm gestures based on the gestural composition. The accelerometer module controlled the low-frequency beating that imitates the music word in sign language. Similarly, the magnet modules are both placed inside and outside the palm that offered finger bending to add and subtract sound engines and finger tapping outside the palm to capture two hand gestures. These finger tapping or closing gestures trigger individual low-frequency drones and clear all the sound engines; show and empty words in sign language respectively.

Embedding the electronic and structural components into the 3D printed parts of this gestural interface allowed us to create small-sized compact interfaces, offering easy and comfortable hand gesture interaction. The versatility also allowed combining individual parts in multiple ways according to the gestural composition.

4.2 Augmenting Instruments with Structural Electronics

Some of the modules discussed in Section 4.1 are repurposed in augmenting existing musical instruments. In this section, we provide an example of extending an alto flute with embedded structural electronics. Figure 5 shows the embedded microphone attached to the mouthpiece and the embedded accelerometer at the footjoint that is used to capture the ancillary gestures of the performer. The microphone is placed in a ring-shaped attachment piece to pick up articulations and the nuances on the breath control. The extension adds complexity to the design for both augmentation and sensor embedding; yet, it offers more flexible and comfortable playing possibilities. Similarly, the accelerometer is embedded into the attachment piece during the print and allows for detecting the musician's movements.

The motivation behind this augmentation draws from the composer's need for triggering the percussive samples with the breath articulations without an external drum pad. The microphone with amplifier in Figure 2b and 5 detected the breath pressure. The accelerometer module was attached to the very end of the flute to capture more variations in the performer's movement. The acceleration data used in controlling the articulations of the processed percussive samples. One of the main advantages of embedding two sensors into one-piece sensor attachments was creating a lighter augmentation and sturdy fixture. The interface aims not to interfere with the natural musical interaction of the flute player.

This particular design proposes several manufacturing challenges in creating the 3D model: 1) determining print angles to successfully embed the electronic parts, 2) customizing the support structure, and 3) predicting the stop

Figure 5: Embedded microphone and accelerometer modules are used to pick up subtle articulations of the musician. This augmentation eliminates the use of any adhesives and allows for easy assembly and disassembly.

layer. The main constraint arises from the need to keep the electronic component protected from the nozzle movement. Since the print head increases the nozzle height layer by layer, the surface of the model after embedding components should be at the same level (or lower) than the current layer height that the pause is scheduled at. This constraint requires keeping the housing parallel to the print bed, adjusting the model in possibly non-ideal positions and angles. Figure 2b shows the attachment piece printed in the upright position to enable the print for embedding. Consequently, this particular part placement necessitates 3D modeling and slicing modifications. While a steadier print and smoother surface finish can be achieved in an orientation where one of the holder arms laying on the build plate, in order to keep the breakout housing parallel to the nozzle movement plane, the part needs to be printed while standing on its arms as shown Figure 6. Realizing this configuration requires customization of the support structures for both blocking the support structure where the microphone needs to be placed and adding a custom support structure on the base of the piece (see Figure 6). Although the complexity of the structure requires several modifications in slicing the 3D model as well as in preparing the G-code, it allows cleaner, compact, and adjustable augmentation.

After these necessary adjustments in the slicing software, determining the print layer becomes more challenging to predict. Either subtracting the top layer height from the total height of the model or previewing individual layers after slicing the model (Figure 6) to observe where the sensor's enclosure begins could provide more convenient methods for calculating the pause height. While the first might give faulty data due to complex shapes where the top layer might be higher than the embedded sensors' enclose height, we observed that the latter offers a more reliable method.

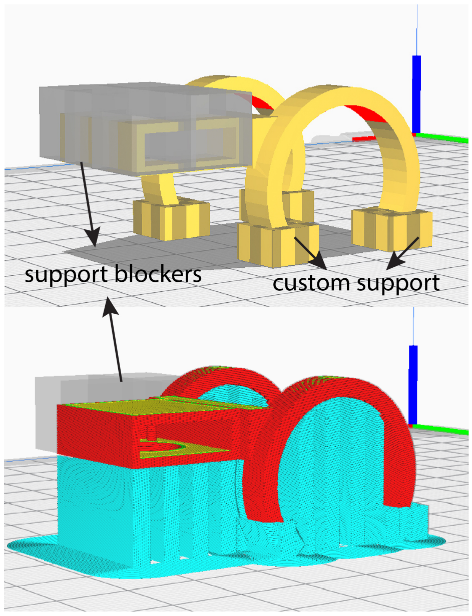


Figure 6: The mouthpiece attachment requires customization of the support structures such as support blockers and additional custom supports.

5. DISCUSSION AND FUTURE WORK

5.1 Uses Cases in DMI Design

The increasing trend in the movement-based interfaces and adopting the body as the musical instrument requires small-scale, compact, and customizable wearable and prosthetic interfaces. These interfaces are treated in many forms: as a prosthetic instrument [14], wearable interface extending the instruments [26], textile attachments [27], or glove-like interfaces [28]. These instruments—interacted with movement—need compact and sturdy interfaces. The approach of embedding electronics can offer interface designers to create versatile gestural controllers and attachment pieces, yet not explored by the music research community.

In our two case studies, we observed that embedding electronics components allowed a more attentive but faster prototyping process since the embedding process is precise and programmable. The process needs to be monitor during the embedding time periods. Still, this process can be predicted from the code modification process. Another limitation of the current study is that the wiring process is not included in the printing. For wireless interfaces, the complexity of embedding geometry and wiring increases, which we aim to address in future work. For both instruments, the sensor modules are printed in one piece which facilitates a smaller and cleaner finish of interfaces. We adopted this technology into designing musical interfaces using individual modules; however, the embedding can be adopted to integrated hardware designs.

Another challenge draws from the limited amount of resources and design frameworks. Although hybrid methods are explored by researchers for non-musical applications [10–12], the lack of high-end printing technology as well as detailed design methodology challenges music instrument designers. In this work, we aim to provide the details of one of the hybrid AM processes using commonly used and affordable 3D printers. Our focus on gestural controllers and augmented instruments could be extended to laptop instruments, controllers, improving embedded instruments, bio-sensing or bio-feedback instruments, etc.

5.2 Customizing with Modular Design

Two instruments presented in this paper demonstrated the proof of concept for incorporating digital sensors into additive manufacturing for music applications. The extent of this technology is not limited to but explores the modular design approach when prototyping gestural controllers for DMIs and traditional instrument augmentation modules. The modular design allows users to construct and customize a wider range of interactions. Among the prototypes we developed, we observed that when this design model is adopted to gestural controllers, prosthetic design, and augmentation of musical instruments, it offers more compact and flexible interactions as well as a cleaner finish. Felt Sound demonstrates the functionality and advantages of the modular sensing systems by allowing the performer to combine the modules in various configurations for capturing different gestures.

5.3 Cleaner Finish

Embedding electronics into the sensor modules allowed us to create more complex shapes for adhesive-free and cleaner assembly in augmenting instruments without interfering with the instrument's capabilities. Although adhesives (glue, tape, velcro, etc.) do not offer substantial attachments and clean surface finishes, they are one of the most widely used augmentation tools to connect sensors to the instrument bodies. Avoiding adhesives allowed us to create more sustainable and aesthetic physical designs. As moving forward, we envision embedding electronic circuitry and sensors in more complex geometries for both prosthetic and/or wearable controllers as well as augmenting traditional instruments.

5.4 Future Directions

The goals of our approach to embedding structural electronics into 3D printed parts have been both to adopt this new AM technology into new musical interface design as well as explore how the availability of the targeted tools influence DMI prototyping and design process. Due to its affordability and accessible resources, we chose FDM technology to test this design idea and its technical specifications.

Additionally, the continuation of this project leverages FDM type printers' ability to print with water-soluble and conductive filaments. The water-solubles are used to print support structures, which are easy to remove. In this ongoing project, we have been further implementing printing wiring structures with water-soluble support material and infusing conductive ink once the support is cleaned. Due to the challenges that come with curing conductive ink, in this paper, we only demonstrated the stop-and-go method with external wiring. However, the future work of this research includes extruding conductive material for both capacitive touch sensing and direct-wiring—wiring the electronic components of the circuitry to each other during 3D printing [8].

6. CONCLUSIONS

In this paper, we present a methodology to adopt embedding electronic structures and functional parts into additive manufacturing (AM) for digital musical instrument (DMI) prototyping. We provide the operational sequences and tools for instrument designers to prototype their embedded electronic designs with affordable AM devices. The 3D printed parts demonstrated in this research are manufactured with fuse deposition modelling (FDM), one of the most widely used 3D printing technology that is accessible to students and researchers as well as individual designers.

We showcase the capability of this technology for music instrument manufacturing through prototyping a wearable gestural controller and an augmented alto flute. Our process further allows the users to design customized interfaces by connecting modular sensors and passive components in combination. The modular design in these two case studies is applied to demonstrate the proof of concept and can be extended to more complex models. This project presents an on-going research on different methodologies to incorporate electronic structures into AM process. Continuing work explores multi-material 3D printing with conductive materials for designing capacitive sensing and with water soluble support structures for conductive ink infusion.

Acknowledgments

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