DIGITAL MANUFACTURING FOR MUSICAL APPLICATIONS: A SURVEY OF CURRENT STATUS AND FUTURE OUTLOOK

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ABSTRACT

In the design of new musical instruments, from acoustic to digital, merging conventional methods with new technologies has been one of the most commonly adopted approaches. Incorporation of prior design expertise with experimental or sometimes industrial methods suggests new directions in both design for musical expression and development of new manufacturing tools.

This paper describes key concepts of digital manufacturing processes in musical instrument design. It provides a review of current manufacturing techniques which are commonly used to create new musical interfaces and discusses future directions of digital fabrication which are applicable to numerous areas in music research, such as digital musical instrument (DMI) design, interaction design, acoustics, performance studies, and education. Additionally, the increasing availability of digital manufacturing tools and fabrication labs all around the world make these processes an integral part of the design and music classes. Examples of digital fabrication labs and manufacturing techniques used in education for student groups whose age ranges from elementary to university level are presented. In the context of this paper, it is important to consider how the growing fabrication technology will influence the design and fabrication of musical instruments, as well as what forms of new interaction methods and aesthetics might emerge.

1. INTRODUCTION

The musical instrument design process requires numerous artistic, musical and engineering design specifications from software design to electronics, from mechanical functionality of instruments and fabrication to compositions and performances. Cather et. al. states that "The lack of a complete and thorough written specification is now generally accepted as being one of the main reasons for design failure" [1, 2]. Commonly, the physical design, mechanical functionality, and rapid manufacturing concerns do not always become the priority of the instrument designers while new musical instruments experience limitations in fulfilling their purposes in the long term. These instruments, even though they are designed for professional use, most of the time, become restricted to be performed in research labs, demos, and recording sessions [3]. In order to increase their professional and artistic use in the long term, designers aim to embody many qualities of traditional instruments in new interfaces with existing fabrication and rapid prototyping techniques. As a consequence, the growth and advancement in digital fabrication techniques create a dynamic interaction between the research, arts, design and education fields.

Efforts in musical instrument design with digital manufacturing are divided into two areas; one performed by those experimenting new fabrication tools to manufacture acoustic instruments, and the other mostly explored by researchers who develop new interfaces, digital, augmented, or hybrid musical instruments. In the first case, the craftsmanship and knowledge on musical acoustics are crucial; yet, the instrument making process still requires other skills that relate to musical expression, aesthetics, and the interaction. On the other hand, researchers either leverage existing manufacturing techniques in unique ways for musical purposes or they develop new tools and advance the technology for higher quality instruments and interactions. This leads to an increasing demand for fast and accurate prototyping tools in designing new interfaces for musical expression.

This paper offers an overview of the current digital manufacturing techniques used in musical instrument design and discusses the application areas of the emerging fabrication tools in new musical expression. The next section, *Section 2*, introduces the field of digital fabrication giving prior examples from researchers, instrument makers, and musicians. *Section 3* discusses the future direction of digital fabrication as well as the possible application areas of the existing technology which is still unknown or uncommon in music and instrument design research. It further summarizes the emerging use of digital manufacturing in music education, examples of fabrication labs and musical instrument design classes.

2. MANUFACTURING MUSICAL INSTRUMENT

2.1 Rapid Prototyping

2.1.1 Additive Manufacturing

Additive manufacturing (AM), also known as 3D printing, is a form of rapid prototyping which creates 3D objects by applying materials layer upon layer [4]. AM, still a rapidly growing technology, is now available for personal and commercial use, as well as for research and education. The decrease in the cost of the technology also leads music researchers, interface designers, and instrument builders to adopt 3D printing into their design process, allowing customized utilization of these technologies.

Figure 1. Hovalin, the 3D printed violin [5].

Earlier examples of instrument manufacturing based on 3D printing are mainly limited to acoustic violin, guitar, and flute fabrications [5, 6]. Hovalin [5] is one of the earliest examples of the 3D printed instruments, which provided a sustainable violin model (Fig. 1). After a number of iterations, designers could propose a model that can be printed without any support structure. Since the layers are supported by the layers beneath them, a model with overhangs (structure with no support below) requires an additional 3D printing support structures to ensure a successful print. Printing an acoustic instrument without support as Hovalin designers suggested increases the production speed significantly. Due to the dimension limitations of the available tools, the instrument needed to be printed in seven different parts, three of which formed the instrument body. Contrary to Hovalin's assembly method of gluing soundboard parts to each other, the Modular Fiddle was printed in one piece by Openfab PDX [7] whose source files are still available for personal manufacturing purposes. According to the designer, because of the single-piece instrument body, the sound is louder and richer than the earlier versions; yet, the sound quality is still not compatible to the mediocre versions of wooden instruments.

Specifically, the earlier versions of 3D printed objects were likely to have certain drawbacks, such as limitations in acoustic qualities and durability. Due to the type of material used in printing, these instrument shapes were deformed over time. Instrument bodies that needed to be printed in multiple pieces due to the printer dimensions also resulted in significant timbral changes. Previously, these technologies could only offer a limited selection of materials which directly affects the acoustics of printed instruments, as well as its tension resistance. An acoustic violin printed in the Formlabs offered black, white, and tough resin, new materials which brought a more stable structure and a cleaner finish. Yet these instruments printed in Formlabs still posed deformation problems of the neck warped under string tension [8]. Despite the drawbacks of the recent technology, these attempts made 3D printing technology available to the do-it-yourself (DIY) and maker communities, resulting in an increased in research of new materials, different printing patterns, and advanced manufacturing technologies. Additionally, these attempts developed a maker community to share open source designs which can enhance personal manufacturing in the long term [9].

Relatedly, designing for AM comes in many different forms in terms of the variety of material, core technology, cost, or print time. Although the process extending from the design to the end product follows a similar path, 3D printing techniques differ in the technology behind them such as stereolithography (SLA) technology, digital light processing (DLP), and fused deposition modeling (FDM). These became more accessible for personal manufacturing, mainly because of economic reasons. On the other hand, researchers started to explore new acoustic instrument designs with advanced printing technologies like Binder Jetting or PolyJet [10]. These machines differ in material choices, resolution, and how they apply the support materials, which are crucial in musical instrument acoustics. The use of new materials in printing to improve the acoustics provided opportunities to decrease the chamber's size while preserving the loudness of the instrument based on cell structured assembly [11]. The 3D printed flute [10] adopted an inject printing technology which could infuse materials with different properties simultaneously in a single build with higher resolution rates (Fig. 2). Despite the fact that the PolyJet technology improved some of the limitations FDM posed like cracking between layers, high tolerance, lower resolution, and non-airtight walls, it still cannot eliminate the material decomposition problem fully.

Figure 2. The 3D printed flute manufactured with the PolyJet technology [10].

For these reasons, PolyJet offers a great technology for prototyping, yet not for manufacturing [10]. This led the researchers to direct efforts in manufacturing new forms of instrument parts such as valves, mouthpieces, or unconventional tonal series [10, 12–16]. The motivation behind these research work not only demands overcoming the limitation of the current manufacturing technologies to create complete working instruments, but also it encourages instrument designers and researchers to experiment creative, artistic interaction methods, explore customized tuning in addition to new solutions for improved ergonomics, acoustics, and aesthetics.

At the current state, despite the availability of new fabrication tools, acoustic instrument production still requires great human effort in modeling, pre, and post editing. In

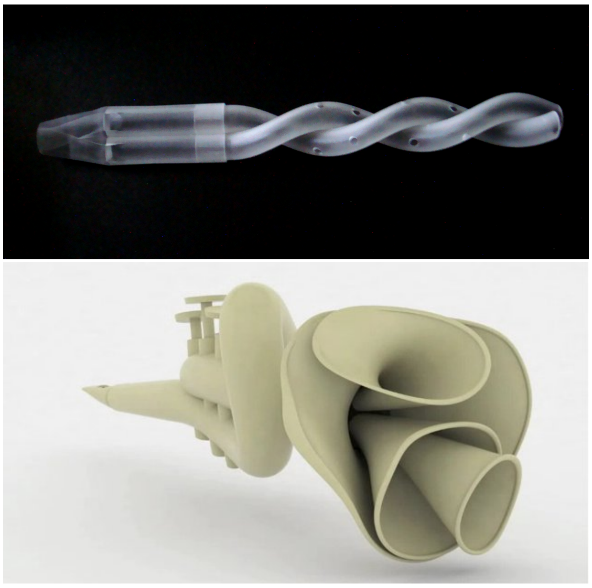

Figure 3. 3D printed double helix flute on top [13], a trumpet with multiple tubes of different radii on the bottom [10].

order to enable analyzing the digital models of instruments before materializing them, researchers developed modal profiles computed with the Finite Element Method (FEM) from 3D models of instruments [17, 18]. They proposed a new modal modeling method integrating FEM analysis into the open-source Computer-Aided Design(CAD) environment for computational estimation of the fabricated targets.

Overall, additive manufacturing was not restricted with the acoustic instrument design but also it was extended in the design of professional uses of hybrid and augmented instruments. Some researchers manufactured instrument bodies and used 3D printing with aesthetic concerns in mind [19]. Those projects not solely leveraged the flexibility or the ability of rapid prototyping, but also proved that AM can provide new forms of aesthetics. For example, Michon et al. used these techniques to design hybrid and augmented mobile instruments [20, 21]. Artists, researchers, and designers leveraged the availability of AM tools to customize their instruments in various ways. It also becomes an integral part of the design for bodily interactions in artistic performances [3].

2.1.2 Subtractive Manufacturing

Subtractive manufacturing is the process by which 3D objects are constructed by successively cutting material away from a solid block of material [22]. Although SM tools such as laser cutters, vinyl cutters, or CNC milling machines, are still an important part of the instrument design process, as opposed to additive manufacturing, these processes have less common use among the new musical interface researchers and designers. This is mainly because of the lack of availability of SM tools in music research labs or their requirement of technical knowledge of machinery use. The existing examples are mostly guitar designs manufactured with wood CNC machines and aimed to improve acoustic characteristics of the instrument by high accuracy of the tools [23].

Additionally, some examples of instruments created in this realm prove that the application of this manufacturing method is not restricted with production purposes but also concern aesthetics and customizable interactions. A commercial carbon fiber guitar was designed and fabricated using milling machines [24] (Fig. 4). *Pipeline*, a brass pan flute with customized tuning, was manufactured using a combination of subtractive manufacturing techniques including rotary milling, turning, and laser cutting [25] (Fig. 5). Subtractive processes, in contrast to 3D printing, do not always offer flexibility; rather, they constrain design freedom due to the need for fixtures, diverse tooling, and the difficulty of the cutter in reaching deeper locations when fabricating complex geometries [26, 27]. For example, the initial design of the *Pipeline* had to be modified due to the dimensions and fixture limitations of the rotary table.

In general, SM becomes a priority when metal pieces need to be processed. Although the innovations in additive manufacturing started to offer 3D printing metal materials, in many cases, CNC post-machining is required to create fine features such as threads, to ensure functionality, and for surface finish [28]. The combination suggests an emerging and efficient fabrication method; hybrid manufacturing which is discussed in *Section 2.3*.

Figure 4. The carbon fiber acoustic guitar manufactured by using advanced composites and machining techniques [24].

2.2 Industrial Manufacturing

Some of the industrial manufacturing processes such as injection molding are used to build instrument parts or bodies. This technique provided the flexibility in designing forms and allowed musicians to experiment with new materials in their design and. It offers an efficient tool for rapid prototyping of multiple identical parts. Because the creation of industrial manufacturing tools (jigs, molds,...) are expensive and time-consuming, these processes are less common as personal manufacturing tools [3]. Ted Brewer's violin is an example of manufacturing the instrument body for his electric violin using injection molding [29]. Other examples are Weinberg and Aimi's Beat-bugs [30], which were cast in clear urethane from rubber molds. These examples of injection molding focused on designing instrument bodies for electric instruments rather than acoustic instruments. Rautia and Koivurova reported that "Non-enforced plastics commonly used in injection molding of the body of an electric guitar are acoustically not as good

Figure 5. Pipeline: brass pan flute with customized tuning [25].

as wood” [31]. Again these instruments are results of musicians or designers collaborating with the manufacturers from the industry rather than personal fabrications. An interesting example of an iterative prototyping method bridging between the industrial manufacturing and personal fabrication could be Kalo and Essl’s approach of fabricating cymbals using incremental robotic sheet forming [32].

Similarly, acoustruments provided a design method which made the manufacturing possible by combining 3D printing with injection molding. The passive acoustically driven handheld devices are iterated by 3D printing for rapid prototyping purposes and suggested that the manufacturing of these toys can be extended to injection-molding for high-volume, low-cost fabrication [21].

2.3 Hybrid Manufacturing

The term of hybrid manufacturing refers to the fabrication methods and technologies which combine different processes including additive, subtractive, or other (joining, dividing, transformative, ...) manufacturing processes on the same machine. The main advantage of this emerging technology is that it offers freedom of additive manufacturing while retaining the precision and surface finish quality of CNC, as well as reducing the dependence on a single process. This freedom unlocks the limitation of 3D printed instrument fabrication using multi-tasking machines. There are some examples of automating existing manual fabrication methods for musical applications. For example, Kalo and Essl used incremental robotic sheet metal forming to form cymbals [32]. Their contribution complements commonly used methods like 3D printing; yet, hybrid manufacturing, as a newly growing field, still lacks examples of musical instruments manufactured this way.

Hybrid manufacturing is progressively becoming common with the use of machinable materials for 3D printing, mainly for purposes like decreasing tolerance and speeding up processes. New machines which can apply both AM and SM on the same run offer better prototyping opportunities for musical instrument design research. Additionally, the fine features and surface finishes of instruments can easily be achieved with hybrid approaches. Yet, it is likely that it will take time for these tools to find their place in the research labs [22].

2.4 Digital Manufacturing & Electronics

An integral part of the new interface design is the electronic construction of digital and electric musical instruments. In addition to reliable mechanical systems that new manufacturing techniques allow designers to realize, the electronic construction has a big influence on robustness, functionality, reliability, and durability of instruments [2, 3]. For stable and robust electronic circuits, designers use printed circuit boards (PCB). This technology is getting extended to printable electronics with new advancements in manufacturing of numerous sensing mechanisms [33]. The printable electronics offer easier constructions for embedded and wearable musical instruments. An earlier work of a wearable musical instrument which used additive and PCB manufacturing is Hattwick and Malloch’s prosthetic instruments [3]. As in similar wearable musical interfaces, the printed circuit technology open us new opportunities for end products in professional and artistic use since it provides low-cost, easy-to-use electronic circuits manufacturing. It further extends the tools to print flexible electronic components and sensors which are light-weight, ultra-thin, stretchable, bendable, and easy to operate in high mobility applications [34].

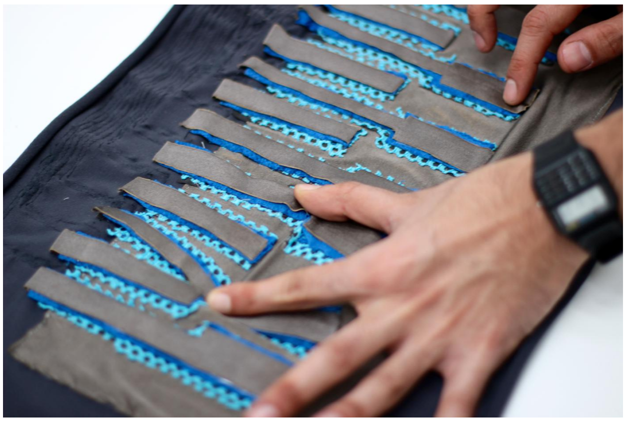

Figure 6. The fabric keyboard is built with multi-layer textile sensors machine-sewn in a keyboard pattern [35].

Subsequently, the manufacturing tools for flexible electronics led the designers to build improved designs of wearable instruments. Wicaksono and Paradiso explored a multimodal, fabric-based, stretchable keyboard for physical interaction based on “deformable musical interface” which detects different stimuli such as touch, pressure, stretch, proximity, and electric field [35] (Fig. 6). Similar to [35], researchers in the interaction design community built several multi-touch textile sensors for music performances [36, 37]. This manufacturing type could be one of the most available manufacturing methods, after additive manufacturing, which could free instrument designers and builders to depend on a particular manufacturer.

Freed reports that the difficulties faced during the experience of building Wessel’s Slabs became a motivation to adopt new technologies that resulted in new designs and new materials for piezoresistive pressure and position sensing surfaces [38]. Wessel's prediction about the printable electronics with Inkjet technology [33, 34] in musical instrument design is nowadays advanced to producing flexible tactile sensor using additive manufacturing techniques [39].

AM with embedded electronic components in the print offers a new manufacturing method in prototyping electronic circuits. In the near future, 3D printing electronics can offer a cost-effective and scalable fabrication technique as an alternative to conventional fabrication methods, most of which are complex, expensive and time-consuming [39]. Hybrid AM processes provide not only improvements for the form and appearance of final products, but also for electronics functionality with embedding most commonly used digital elements of DMIs (passive sensors, accelerometers). Fig. 7 gives a simple example designed using CAD modeling tools and prototyped with AM process [40].

Figure 7. Gaming dice with electronic circuit mechanically designed into substrate. It consists of a micro-controller, MEMS accelerometer, batteries and LEDs [40].

Whereas there has not been an example of this technology in the musical instrument design, not to the extent of author's knowledge, the growing interest in designing digital musical instruments and interfaces with 3D printing tools creates room to incorporate the electronic construction in the existing manufacturing processes. As a new technology, 3D printing electronics currently has limitations like complexity, time demand, higher cost. Hopefully, with more cost-effective machines, manufacturing light-weight, and compact flexible/stretchable electronics in fabrication labs will not only help to develop new interaction methods but also encourage designers to develop wearable interfaces for intermedia performances like combinations of music, dance, and theater.

3. FUTURE APPLICATIONS

Musical instrument design requires a lot of hands-on study in the fabrication labs (FabLabs). As the manufacturing tools have become affordable, higher number of fabrication labs have been founded in the academic makerspaces, and universities and research institutions have begun to offer more musical acoustics and instrument design classes [41–44]. Access to the manufacturing tools, specifically to 3D printers and laser cutters, brings fabrication processes to the classroom not only for university-level students but also for the primary school students. Harriman emphasizes the importance of digital musical instrument design in children's education [45], and Eisenberg discusses the challenges in the way of incorporating digital manufacturing into the classroom for children [46]. On the other side, researchers direct their efforts to design portable digital manufacturing tools to reach less accessible parts of the world [47].

One of the changes occurring in the digital fabrication area is in hybrid manufacturing. Although as of now there are some examples of hybrid manufacturing, there are a lot of improvements needed in this area, specifically for more cost-effective tools. Musical instrument design could benefit this technique in various ways by combining most commonly used techniques either for fast prototyping or for end products. These tools, in addition to portable digital manufacturing tools, can also enhance personal fabrication and change the modalities of industry-academia collaborations. Hybrid approaches are not limited to combinations of manufacturing tools; virtual reality (VR) is becoming one of the main tools that researchers merge into fabrication education and cloud control. Researchers use VR simulations for remote control or teaching purposes which accelerates the need for tactile sensors and haptic feedback mechanisms in VR tools generally. On the other hand, fast prototyping opportunities, which come with advanced digital manufacturing tools, propose customizable controllers for VR to overcome the human sensory limitations. The interaction between the two fields can be beneficial for both areas in creating interactive tools and opening up new opportunities.

While manufacturing and material science provide new ways of fabricating instruments, researchers are finding promising results with acoustic modeling of fabricated instruments. With improved computation of 3D data, 3D scanners can be used in modal analysis of manufactured instrument by reverse CAD modeling. Unfortunately, the current state of the professional 3D scanners still poses challenges in obtaining accurate models. The technology requires post-processing of the scanner data before FEM simulation.

4. CONCLUSIONS

While the design capabilities with the fabrication methods discussed in this paper depend upon the financial and institutional infrastructures, digital manufacturing tools are becoming available with a greater variety and frequently used in music research and education. This paper discusses the current digital fabrication techniques used in musical instrument design. It presents an overview of what future directions are available and how they can be applied to musical instrument making and artistic interaction design.

The innovations creating new opportunities for musical expression are not limited solely to the manufacturing processes. New materials can provide better acoustics or more playable and robust musical instruments. The research conducted in this area such as print composites of wood and polyester, or bio-composites are not covered in this paper.

5. REFERENCES

[1] H. Cather, R. D. Morris, M. Philip, and C. Rose, *Design engineering*. Elsevier, 2001.

[2] I. Hattwick and M. M. Wanderley, "Design of hardware systems for professional artistic applications," in *Proceedings of the 17th International Conference on New Interfaces for Musical Expression (NIME-17)*, 2017.

[3] I. Hattwick, J. Malloch, and M. M. Wanderley, "Forming shapes to bodies: Design for manufacturing in the prosthetic instruments." in *Proceedings of the 14th International Conference on New Interfaces for Musical Expression (NIME-14)*, 2014, pp. 443–448.

[4] C. K. Chua and K. F. Leong, *3D Printing and Additive Manufacturing: Principles and Applications (with Companion Media Pack) of Rapid Prototyping Fourth Edition*. World Scientific Publishing Company, 2014.

[5] Hovalabs. Hovalin website. [Online]. Available: http://www.hovalabs.com/hova-instruments/hovalin

[6] S. Summit, "System and method for designing and fabricating string instruments," Dec. 13 2016, uS Patent 9,519,733.

[7] O. P. Perry, David. Modular fiddle. [Online]. Available: https://openfabpdx.com/modular-fiddle/

[8] B. Chan. Designing a 3D Printed Acoustic Violin, Formlabs. [Online]. Available: https://formlabs.com/blog/designing-a-3d-printed-acoustic-violin/

[9] J. Walter-Herrmann and C. Büching, *FabLab: Of machines, makers and inventors*. transcript Verlag, 2014.

[10] A. Zoran, "The 3D printed flute: digital fabrication and design of musical instruments," *Journal of New Music Research*, vol. 40, no. 4, pp. 379–387, 2011.

[11] A. Zoran and P. Maes, "Considering virtual & physical aspects in acoustic guitar design." in *Proceedings of the 8th International Conference on New Interfaces for Musical Expression (NIME-08)*, 2008, pp. 67–70.

[12] S. Leitman and J. Granzow, "Music maker: 3D printing and acoustics curriculum," in *Proceedings of the 16th Conference on New Interfaces for Musical Expression (NIME-16). Brisbane, Australia*, 2016.

[13] M. Dabin, T. Narushima, S. T. Beirne, C. H. Ritz, and K. Grady, "3D Modelling and Printing of Microtonal Flutes," in *Proceedings of the 16th International Conference on New Interfaces for Musical Expression (NIME-16), Brisbane, Australia*, 2016, pp. 11–15.

[14] N. J. Bailey, T. Cremel, and A. South, "Using acoustic modelling to design and print a microtonal clarinet," in *Proceedings of the 9th Conference on Interdisciplinary Musicology (CIM14), Berlin, Germany*, 2014, pp. 4–6.

[15] J. Granzow, "Additive manufacturing for musical applications," Ph.D. dissertation, Ph.D. Thesis, Stanford University, Stanford, CA, USA, 2017.

[16] V. Lorenzoni, E. Doubrovski, and J. Verlinden, "Embracing the digital in instrument making: Towards a musician-tailored mouthpiece by 3D printing," in *Proceedings of the Stockholm Music Acoustics Conference 2013, SMAC 2013, Stockholm (Sweden), 30 July-3 August, 2013*, 2013.

[17] R. Michon, C. Chafe, and J. Granzow, "3D Printing and Physical Modeling of Musical Instruments: Casting the Net," in *Proceedings of Int. Conf. Sound and Music Computing (SMC-18)*, 2018.

[18] N. Plath, "3D Imaging of Musical Instruments: Methods and Applications," in *Computational Phonogram Archiving*. Springer, 2019, pp. 321–334.

[19] E. Goldemberg and V. Zalcberg. Monad studio. [Online]. Available: https://www.monadstudio.com/About-MONAD-Studio

[20] R. Michon, J. O. Smith, M. Wright, C. Chafe, J. Granzow, and G. Wang, "Mobile music, sensors, physical modeling, and digital fabrication: Articulating the augmented mobile instrument," *Applied Sciences*, vol. 7, no. 12, p. 1311, 2017.

[21] G. Laput, E. Brockmeyer, S. E. Hudson, and C. Harrison, "Acoustruments: Passive, acoustically-driven, interactive controls for handheld devices," in *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 2015, pp. 2161–2170.

[22] Z. Zhu, V. G. Dhokia, A. Nassehi, and S. T. Newman, "A review of hybrid manufacturing processes–state of the art and future perspectives," *International Journal of Computer Integrated Manufacturing*, vol. 26, no. 7, pp. 596–615, 2013.

[23] A. Krimpenis and M. Chrysikos, "3D parametric design and CNC manufacturing of custom solid wood electric guitars using CAD/CAM technology," *Wood Material Science & Engineering*, pp. 1–15, 2017.

[24] B. Guitars, "Blackbird rider acoustic," 2008.

[25] D. Cavdir, "Pipeline:custom tuned brass pan flute," 2018. [Online]. Available: http://www.dogacavdir.com/pipeline-si5x

[26] K. Karunakaran, A. Bernard, S. Suryakumar, L. Dembinski, and G. Taillandier, "Rapid manufacturing of metallic objects," *Rapid Prototyping Journal*, vol. 18, no. 4, pp. 264–280, 2012.

[27] W. Gao, Y. Zhang, D. Ramanujan, K. Ramani, Y. Chen, C. B. Williams, C. C. Wang, Y. C. Shin, S. Zhang, and P. D. Zavattieri, "The status, challenges, and future of additive manufacturing in engineering," *Computer-Aided Design*, vol. 69, pp. 65–89, 2015.

[28] W. E. Frazier, "Metal additive manufacturing: a review," *Journal of Materials Engineering and Performance*, vol. 23, no. 6, pp. 1917–1928, 2014.

[29] K. R. Zappas, "The science of sound: Examining the role of materials in musical instruments," *JOM*, vol. 59, no. 8, p. 13, 2007.

[30] G. Weinberg, "The beatbug–evolution of a musical controller," *Digital Creativity*, vol. 19, no. 1, pp. 3–18, 2008.

[31] V. Rautia and H. Koivurova, "Method for manufacturing musical instrument and a musical instrument," May 8 2007, uS Patent 7,214,866.

[32] A. Kalo and G. Essl, "Individual fabrication of cymbals using incremental robotic sheet forming," in *Proceedings of the 16th International Conference on New Interfaces for Musical Expression (NIME-16)*, 2016, pp. 287–292.

[33] M. Mantysalo, V. Pekkanen, K. Kaija, J. Niittynen, S. Koskinen, E. Halonen, P. Mansikkamaki, and O. Hameenoja, "Capability of inkjet technology in electronics manufacturing," in *Electronic Components and Technology Conference, 2009. ECTC 2009. 59th*. IEEE, 2009, pp. 1330–1336.

[34] Z. Yin, Y. Huang, N. Bu, X. Wang, and Y. Xiong, "Inkjet printing for flexible electronics: Materials, processes and equipments," *Chinese Science Bulletin*, vol. 55, no. 30, pp. 3383–3407, 2010.

[35] I. Wicaksono and J. A. Paradiso, "Fabrickeyboard: Multimodal textile sensate media as an expressive and deformable musical interface," *Proceedings of the 17th International Conference on New Interfaces for Musical Expression (NIME-17), Aalborg, Denmark*, 2017.

[36] J.-S. Roh, Y. Mann, A. Freed, D. Wessel, U. Berkeley, A. Freed, A. Street, and D. Wessel, "Robust and reliable fabric, piezoresistive multitouch sensing surfaces for musical controllers." in *Proceedings of the 11th International Conference on New Interfaces for Musical Expression (NIME-11)*, 2011, pp. 393–398.

[37] M. Donneaud, C. Honnet, and P. Strohmeier, "Designing a multi-touch etextile for music performances," in *Proceedings of the 17th International Conference on New Interfaces for Musical Expression (NIME-17), Aalborg, Denmark*, 2017, pp. 15–19.

[38] A. Freed, "David wessels slabs: a case study in preventative digital musical instrument conservation," *Proceedings of Int. Conf. Sound and Music Computing, (SMC-16)*, 2016.

[39] C. Liu, N. Huang, F. Xu, J. Tong, Z. Chen, X. Gui, Y. Fu, and C. Lao, "3D printing technologies for flexible tactile sensors toward wearable electronics and electronic skin," *Polymers*, vol. 10, no. 6, p. 629, 2018.

[40] E. Macdonald, R. Salas, D. Espalin, M. Perez, E. Aguilera, D. Muse, and R. B. Wicker, "3D printing for the rapid prototyping of structural electronics," *IEEE access*, vol. 2, pp. 234–242, 2014.

[41] V. Wilczynski, "Academic maker spaces and engineering design," in *American Society for Engineering Education*, vol. 26, 2015, p. 1.

[42] T. Bertrand, K. Kaczmarek, and L. Wilen, "Musical acoustics & instrument design: When engineering meets music," in *ICMC*, 2015.

[43] N. Villicaña-Shaw, S. Salazar, and A. Kapur, *The Machine Lab: A Modern Classroom to Teach Mechatronic Music*. Ann Arbor, MI: Michigan Publishing, University of Michigan Library, 2017.

[44] A. Zoran, "Hybrid craft: showcase of physical and digital integration of design and craft skills," in *ACM SIGGRAPH Art Gallery*. ACM, 2015, pp. 384–398.

[45] J. Harriman, "Start'em young: digital music instrument for education." in *Proceedings of the 15th International Conference on New Interfaces for Musical Expression (NIME-15)*, 2015, pp. 70–73.

[46] M. Eisenberg, "3D printing for children: What to build next?" *International Journal of Child-Computer Interaction*, vol. 1, no. 1, pp. 7–13, 2013.

[47] N. Peek and I. Moyer, "Popfab: A case for portable digital fabrication," in *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, 2017, pp. 325–329.