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The 3D Printed Flute: Digital Fabrication and Design of Musical Instruments

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Abstract

This paper considers the controversy of modern acoustic instruments, which may have come to an evolutionary impasse, due to its high standardization that makes it difficult to explore design modifications. A new approach for the design and fabrication of an acoustic instrument is presented, using digital fabrication technologies, and specifically 3D printing, which has the potential to influence new designs, and to lead to new acoustics and ergonomic innovations. This paper describes the key concepts of this approach, presenting the development process of such a 3D printed instrument—a prototype of a 3D printed concert flute, some other 3D printed elements, and a conceptual example of an innovative trumpet—discussing the potential of the new technology in fabricating and designing of musical instruments.

1. Introduction

In traditional musical instrument making, the importance of merging traditional designs and methods with the ability to use new technologies has always been a major theme (Sachs, 2006). The craftsmanship developed around instrument making required skills that were not always directly related to acoustic values of instruments: musical instruments have been profoundly influenced by cultural and aesthetic factors, such as form and decoration. The complex relationship between design, sound, and playability stands at the heart of instrument development: in many cases, sound and playability were limited owing to the constraints of the instrument design, which was limited by the fabrication technologies.

In many cases, modernity has simplified instruments making, optimized production and fabrication processes. Since the Industrial Revolution, new methods have changed the manufacturing of instruments and new materials, such as plastic, are replacing traditional ones. Yet, despite industrialization, producing a high quality acoustic instrument still requires great human craftsmanship; a violin glued together from mass-produced parts cannot equal (acoustically nor aesthetically) one that has been constructed by an individual craftsman who is not satisfied with the work until everything is working together perfectly (Barker, 2001). Despite these differences, both craftsmanship and mass-production processes have a directed influence on instrument designs—for sound, playability, or economic requirements.

The popularity of a specific musical instrument led to a focused design process, improving the instrument's performance and playability step by step. These design iterations, evolving together with the musical style, ends with a well-defined musical tool. This process of standardization occurred in the making of almost any popular instrument in the West, and sometimes led to an increase in the instrument's mechanical complexity and better expressive performance ability. For example, it is more complex to build a grand piano than to build a hammered dulcimer (Williams, 2002); the mechanical keys, which have been added to many wind instruments, made them much more difficult to build than just pipes with holes (Baines, 1991). Together with the increase of standardizations of musical instruments, better skills were required in order to build the instrument, and specific tools and workshops were developed to support this process.

However, the standardization of a musical instrument is a dangerous process. On one hand, it optimized the

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instrument's qualities for the trained player. But it also positioned the instrument on a certain evolutionary path, making it difficult for the maker and the player to adopt new designs. For example, it is easier to change the design of the hammered dulcimer than to change the design of the piano. In the second case, we may need to change the whole factory. But the hammered dulcimer lost its popularity in Europe, after evolving into the harpsichord and then the piano. Today it is not a popular instrument anymore, and a skilled pianist may not know what to do with such a tool. While on one hand technology helped in defining instrument standards, it also has the potential to suggest new directions and possibilities. For example today, many sound design innovations are being achieved using electronic instruments and tools.

Since electrical technology was applied to musical instruments, we see little acoustical and mechanical modification to traditional instruments, and more instruments are becoming electrically amplified, controlled and modified. Yet, there is still a place to experiment with acoustic and mechanical technologies. The unique, authentic and expressive interface of these instruments is still a challenge for the digital ones. Moreover, the aesthetic and sonic coupling of the acoustic instrument may continue to be relevant in the future.

Many works have been done facing the challenges above. The work of Hopkin (1996), for example, presents an alternative classification of instruments, proposing an interesting perspective on the acoustic possibilities for sound creation. His work includes the Membrane Reed (a membrane that is literally pulled to be a pipe), the *Musical Siren* and the *Branching Corrugahorn* (multiple tubes with discreet notes). Hopkin merges traditional acoustic principles, experimental combinations of alternative interfaces, materials, and sound production elements, through a collection of novel acoustic-electric instruments he creates. A different approach is *The Chameleon Guitar* (Zoran & Paradiso, 2011a), a guitar with a replaceable acoustic resonator. This approach is characterized by sampling the resonator's acoustic vibrations with multiple sensors. Then, the sound is processed in a digital processing unit, to achieve the sonic qualities of a big chamber.

This paper comes face to face with the challenge of designing acoustic and mechanical elements using digital fabrication. The motivation of this work is to demonstrate a new fabrication technique rather than improving the current design of the flute, and hoping to inspire instrument makers and musicians. The lessons learned from the process, and the limitations of this technology will be discussed. The next section introduces the field of digital fabrication, as well as discusses related work. Section 3 discusses a case study and the development of prototypes of a printed concert flute—using two different printing technologies (see Figure 1)—and presents the prototypes' designs and evaluations. In Section 4 development of other printed wind instrument elements is presented, and a future vision of using 3D printing technologies in the fabrication of wind instruments is discussed. The last section, Section 5, is a summary of the work and its contribution.

2. Background

2.1 Digital fabrication

In the last 50 years, digital tools have dramatically altered our ability to design the physical world (Gershenfeld, 2005). While the advances that have taken place in graphic software and hardware are no longer a privilege of specialists, the use of 3D printers has remained restricted to a few. However, in recent years, the price of three-dimensional printers has fallen dramatically and several DIY technology groups have started to develop and share their open source 3D printer designs for anyone interested in modifying or building these machines at home (RepRap, 2010). While most of the 3D printing technologies are still limited to rapid prototyping, there is an ongoing research to enable these technologies as a means for rapid manufacturing as well, in order to enable the creation of stronger, functional,

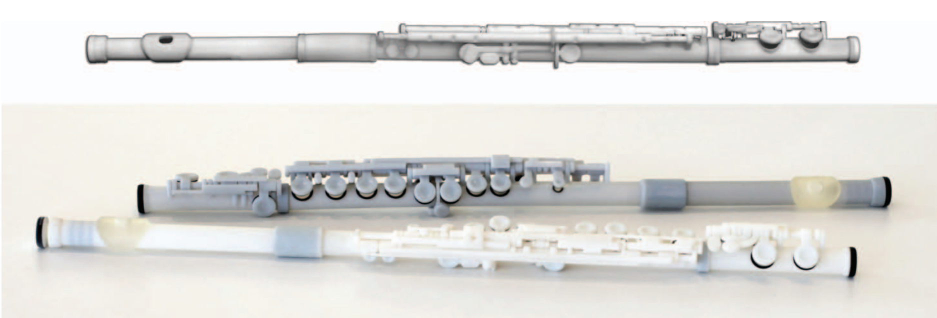

Fig. 1. Pictures of the printed flutes—FDM technology—made from acrylonitrile butadiene styrene (ABS) (top), and PolyJet technology—two flutes, each made from three different materials (bottom).

and reliable artifacts (Hopkinson, Hague, & Dickens, 2006).

Digital fabrication technologies could be grossly grouped under two main areas or approaches: subtractive and additive machines. Subtractive approaches use drill bits, blades or lasers to remove material from an original material source, shaping the desired three-dimensional object. Additive processes, on the other hand, use an array of techniques for depositing progressive layers of material until a desired shape is achieved. As these machines and fabrication techniques become commonplace in our homes, they will drastically affect the types and quantities of objects we own, dramatically altering our relationships with them. A pertinent example is a digitally fabricated mechanical clock (Schmitt & Swartz, 2009), which encompasses all the mechanical complexity of a hand-assembled weighted clock, but is 3D printed as a single machine that requires no human assembly. In the context of this paper, it is important to consider what kind of new aesthetics will emerge from the use of digital fabrication machines and how they will influence the process of design and fabricating musical instruments.

Many 3D printing technologies are being used today (Chua, Leong, & Lim, 2003), such as stereolithography (STL), selective laser sintering (SLS), fused deposition modelling (FDM), and Objet's PolyJet. Some methods already employ a variety of materials, from clay and plaster to many types of plastics or even metals. 3D printing technologies vary in their printing time, construction and support techniques, the price of printing and the resolution and material properties. In this research, two technologies were used and evaluated: Stratasys' FDM and the Objet's multilaterals PolyJet.

2.1.1 Fused deposition modelling (FDM) technology

In the FDM technology, a robotic head places thin layers of ABS plastic (or other thermoplastic polymers) on a tray, and slowly implements a computer-aided design (CAD) model until the final shape is achieved. The FDM process uses a secondary material to support the primary one. After the process is finished, the supporting material is removed using an ultrasonic chemical bath. In the work presented in this paper, two machines were used—the Dimension *Elite* (for most of the elements), and the Fortus *Titan* (for the largest printed element), both made by Stratasys. The resolution of the Dimension machine (the distance between the layers) is limited to 0.17 mm. The Fortus technology is superior to the Dimension one and can produce stronger results with a higher resolution (Stratasys, 2010).

2.1.2 Objet's PolyJet technology

The PolyJet technology by Objet uses inkjet technologies, printing acrylate-based photopolymer that is cured (solidify) using UV light. The Objet Connex500, based on this PolyJet technology, has a unique ability to jet 'multiple model materials simultaneously, printing parts and assemblies made of multiple model materials, with different mechanical or physical properties, all in a single build' (from company's website, Objet, 2010). This property was very useful in the design of the flute (Section 3.3.), allowing the implementation of different mechanical properties to the printed material, in order to create soft areas and rigid ones. The Connex machine uses a supporting material that can be washed away with water (see Figure 2), and its resolution can be higher than 0.1 mm.

2.2 Digital fabrication and the design of the musical instrument

In the past several years, digital fabrication has slowly infiltrated the field of musical instrument making. RedEye RPM, a 3D printing service company (belonging to Stratasys), created a solid body guitar using digital manufacturing technology (RedEye RPM, 2008). Blackbird Guitars made the Blackbird Rider Acoustic, a commercial guitar digitally designed and fabricated (using milling machines) made from composite materials (Blackbird Guitars, 2008). This kind of new material (such as carbon fiber composites) enables a significant

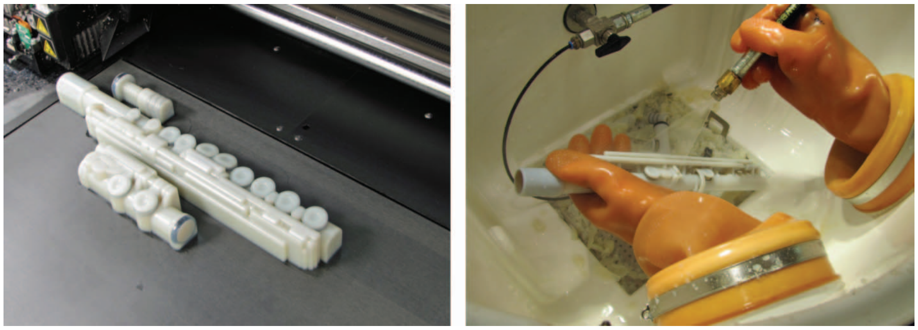

Fig. 2. Printed flute parts by Objet Connex500, covered with support material (left), and the cleaning process (right).

decrease of the chamber's size while preserving the instrument loudness. The *reAcoustic eGuitar* is a concept design, a computer graphic illustration of an idea that players would be able to customize their own sound by assembling different 3D printed sound cells instead of a single large sound box (Zoran & Maes, 2008). Each string has its own bridge; each bridge is connected to a different cell. Changing the cell size, material or structure allows sound design innovations, re-designing acoustic musical instruments according to the abilities and characteristics of rapid prototype materials. The open source and shared files environment can lead to a reality in which a player can download or design his/her own sound cells and add them (as a patch) to her/his instrument.

The 3D printing technologies can be used to produce acoustic and mechanical elements in musical instruments. Today, digital instruments have versatile sound control; however the standardization of traditional acoustic instruments makes it difficult to change them or their sound. 3D printers can introduce a fast, easy to manipulate method to implement changes and to experiment with the design.

2.3 Wind instruments as a case study

Although the flute may be the oldest of all musical instruments, and has roots in the Stone Age, the modern wind instrument evolved in Europe just after the middle Ages (Baines, 1991). Modern wind instruments have been developed in Europe since the seventeenth century. Trumpets and horns were already used in Europe and Asia for military purposes and rituals. The clarinet emerged at the end of the seventeenth century and, like the oboe, developed into a family of instruments. Due to its importance in the European music, the modern wind instrument arrived at a well-defined design standard, achieving a high degree of acoustic control and playability. Today, instrument makers have started to adopt 3D printing as a rapid prototyping technology (Phelan, 2011), mostly to test the design of new parts instead of taking advantages of this technology for manufacturing.

It is complicated to build modern wind instruments. The pitch is usually controlled either by the length or the volume of the air tube, or by changing the air pressure inside the tube (Fletcher & Rossing, 1990). In order to change the pitch, different mechanical solutions have been used—from holes in a pipe (like in a flute), which can be covered by the player's fingers or mechanical keys, to valves that can direct the air through different tubes at different lengths.

The air excitation inside the tube is critical to the timbre, and sometimes also to the pitch. Different instruments use different techniques—from a variety of mechanical mouthpieces to different lip techniques. The material of which the instrument is made of is important (mostly wood or different types of metals), but in general, it is less important than in other instruments such as the violin family, which uses a wood soundboard to vibrate and project the sound.

This paper focuses on wind instruments because of their unique mechanical properties, comparatively small size, and their relatively low sensitivity to the tubes' materials. The bigger challenge was to print the mechanical elements of these instruments—valves, mouthpieces and keys. Here, I present a concert flute as a good case study, due to its scale and high mechanical complexity. This is a proof of concept, which can help us understand the limitations as well as the capabilities of the technology. By analysing the printed flute, the results can help in suggesting of the best way to use the 3D printing technology in the fabrication of wind instruments.

3. The 3D printed flute

3.1 The design process

Each 3D printing technology has different abilities and limitations, and one design for a specific machine does not necessarily fit another. Issues such as tolerance, surface smoothness, resolution, and other material properties have a huge influence on the design. Here, two 3D printing technologies were tested: the FDM technology, and the Objet PolyJet technology, while the flute CAD model was designed usnig Rhino 4.0 software (see Figure 3). The prototypes presented in the following sections are based on a standard concert flute, with the same pipe dimension, hole locations, and key design. However, the mechanical solutions to enable them varied and changed, from one design iteration to another, in looking for an optimal solution. In the following section, I first discuss the experiences and lessons learned from the FDM technology, and then evaluate the Objet Connex500 technology. Objet Connex500 has shown better results in printing the flute, and was the one to produce a working flute with reliable keys.

3.2 The FDM flute

The first design iteration was a fully modelled flute, including all its mechanical keys, pads, and springs, printed in ABS plastic using the FDM technology. Instead of the regular flute pads (that are used to stop the air, and are usually made from fish skin, rubber or felt), a plastic 3D printed pad was designed as an integrated part of the key mechanism (see Figure 4). Due to FDM surface resolution, the surface of the holes and the printed pads was relatively rough, and the air was not blocked properly. Later, glued felt pads were added after the flute was printed to replace the plastic solution. Different types of printed springs were evaluated, but none of them proved a reliable solution for the FDM printing technique, so they were replaced with small metal springs (see Figure 5(b)). Also, ABS rings were printed to reinforce the flute edges and prevent it from cracking between layers, a common problem with the FDM technology (see Figure 6).

The final version of the printed flute had nine different parts, and it took a total of four days to print. After

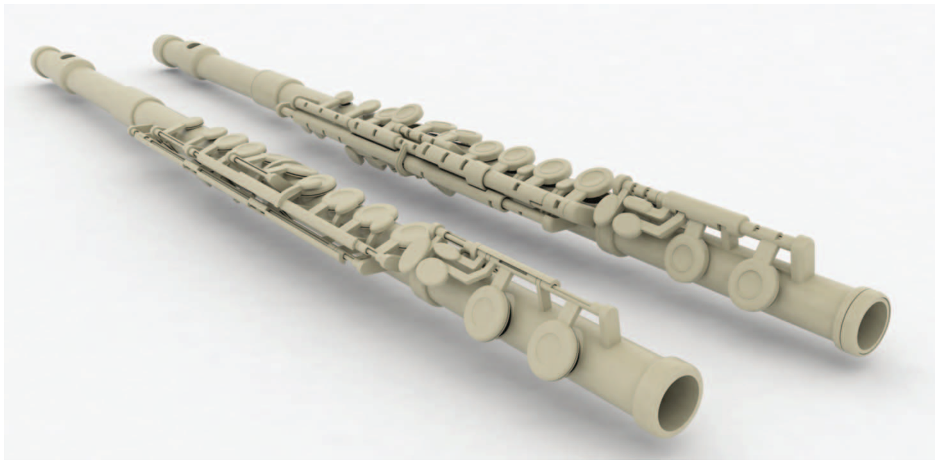

Fig. 3. The first (left) and the last (right) design iterations for the FDM technology. This computer rendering was made using V-Ray software.

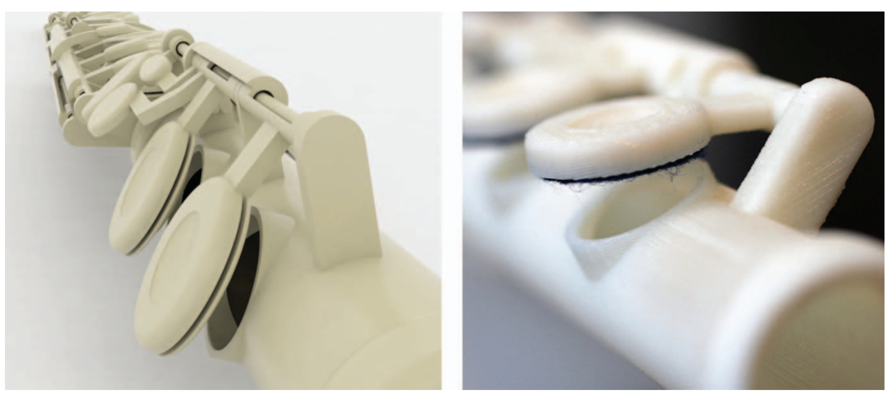

Fig. 4. The design of the printed plastic pads (left), and a picture of the glued felt solution (right) for the FDM flute. The computer rendering in the left was made using V-Ray software.

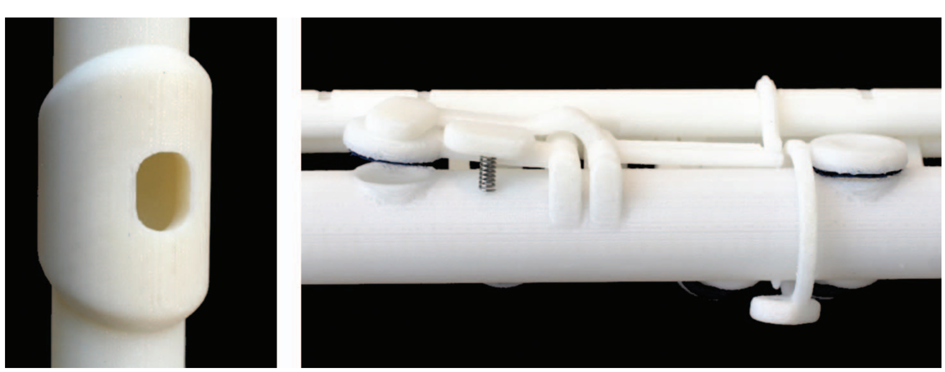

Fig. 5. A picture of the FDM flute's mouthpiece (left) and a key's mechanism, using metal spring (right).

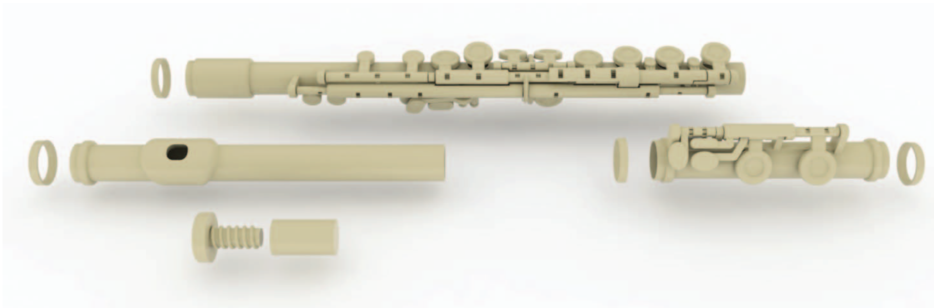

Fig. 6. The design of the nine FDM flute parts. This computer rendering on the left was made using V-Ray software.

gluing the rings around the edges, it contained four parts: the body joint, the head joint, the foot joint, and the crown, as in a regular concert flute. All the mechanical keys were printed directly on the joints, without needing to be assembled. In order to guarantee that the moving parts of the keys will not stick to each other during the printing process, it is important to keep a tolerance that is more than twice the machine's resolution (0.36 mm). The felt pads and the metal springs were inserted at the end of the process.

Because of the relatively loose hinges and the low rigidity of the printed ABS plastic, the main problem in the printed flute was the loss of mechanical energy. The high tolerance in the printing process caused the hinges to be too loose. Using thicker hinges minimized the tolerance and elasticity problems. The last printed version of the FDM flute had much thicker hinge mechanisms, but, due to acoustic and ergonomic constraints, its size is technically limited and could not be thickened further. In this version, some of the keys were still difficult to control. As the length of the lever is longer, more energy is lost in its twisting and torquing, causing less energy to be directed to the movement of the key.

The flute lip plate functioned well and enabled an easy production of sound (see Figure 5(a)). The assembly of the different parts was also easy and the instrument proved itself strong and lightweight. However, because of the problems mentioned earlier, it was difficult to control the instrument's pitch and to use it for musical purposes. More than that, the FDM technology has been shown as unable to produce watertight walls, meaning the flute's pipe allowed for some air flow through the walls. While this is not a serious problem with thick walls, which create sufficient mechanical resistance to the air pressure, the flute's long and thin walls proved problematic.

3.3 The Objet flute

The Object Connex500 technology has a better resolution than the Dimension 3D printer, which helped in minimizing twisting and torquing problems (the tolerance here was 0.2 mm), and the material proved to be watertight even with the flute's thin walls. A unique property of this technology is its ability to jet multiple model materials simultaneously, and the flute was redesigned to be composed of a rigid material for the body, a different, safer one for the mouthpiece, and a soft material for blocking the air properly in the keys, replacing the glued pads (see Figure 7). Only metal springs were added manually later. The overall printing process took around 15 h (15% of the time it took the FDM technology), creating five separate parts that were then assembled into a working instrument.

Similar to the FDM flute, several design iterations were needed to achieve best performance. Here, the flute was able to produce several notes, making it a playable instrument, as can be seen in the project's website (Youtube, 2010). While this is not yet a perfect instrument, the sound it produced has shown high similarity with a regular metal flute. For example, in Figure 8 we see the spectrums' comparison of the B1 note (based on recordings of length 0.3 s which do not include the transient) of a metal flute, a printed flute and a clarinet.

The PolyJet technology has a major disadvantage—the UV cured material slightly decomposes with time. It is a great technology for prototyping but not so much for manufacturing. Three weeks after it was printed, the flute bent 7 mm in its longitude dimension, preventing its mechanisms functioning properly.

4. Pushing the boundaries

The technical properties of the flute keys made it a great platform for experimentations, but it is difficult to play over time due to the limitations of the printing technology. The FDM technology proved not mature enough to produce sufficient flute keys and proper air pipes, and the Objet's PolyJet is not stable for long periods. Several other ideas for 3D printing were tested, including implementing some other mechanical elements of wind instruments that may fit the FDM technology better, such as valves and mouthpieces. Here, the motivation was not to print a complete working

Fig. 7. A picture of the Objet flute's printed pads (soft material in black), printed simultaneously with the flute body and key mechanisms (rigid material in white).

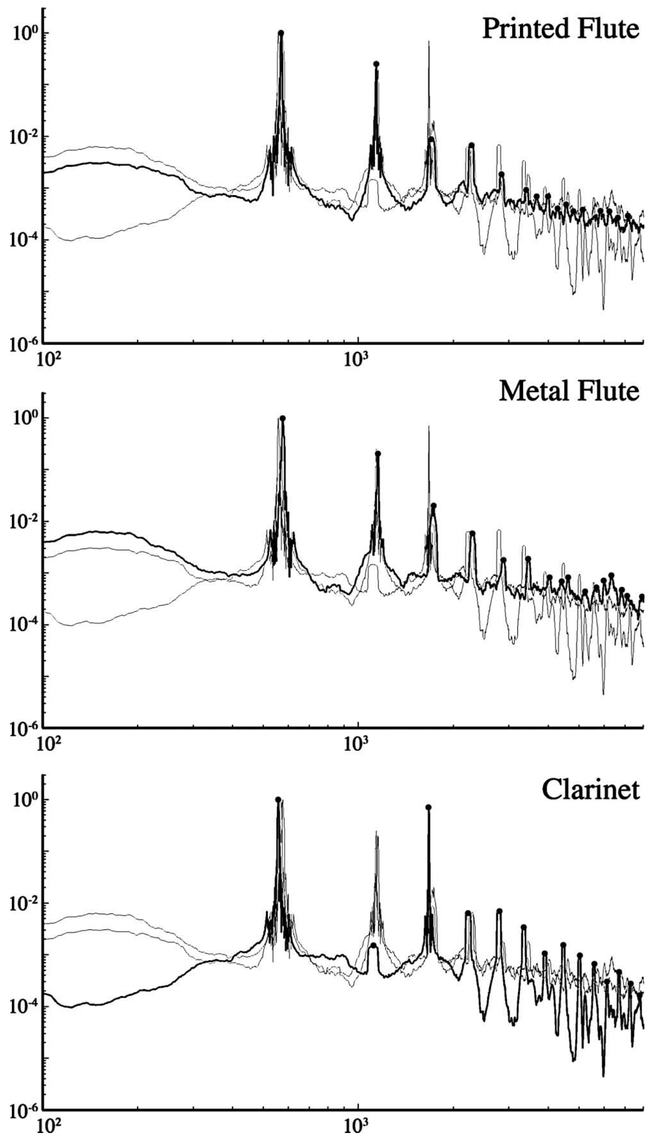

Fig. 8. Logarithmic spectrum comparison of the B1 note, based on recordings of a length of 0.3 s which do not include the transient, of a printed Objet's flute (top), a regular metal flute (middle), and a clarinet (bottom). In each plot the grey graphs are the two other recordings, for reference. The clarinet sound sample was taken from www.compositiontoday.com, and was not recorded under the exact same conditions.

instrument, but to evaluate it in the production of other challenging parts.

Two different valves, which function as air junctions—directing the air in three different directions were printed; as well as several mouthpieces; springs for the valves; and a bell (see Figure 9). The valves (after two design iterations) worked properly with metal springs and felt between the moving parts (to make the motion smooth and easy). With the linear movement of the valves, twisting and torquing problems were not an issue. The printed springs failed to carry a load and were not flexible, and as before, were replaced by metal ones. The mouthpieces and bell functioned properly, as static elements with no moving parts.

This process showed that while it is still challenging to fabricate a complete, stable traditional instrument, new mechanisms and ideas, which were designed especially for the new technologies, have a higher chance of success. Thicker walls can help in resisting the air better, linear motion doesn't suffer from twisting and torquing and is less sensitive to tolerance, and static elements (such as the mouthpiece) cannot fail. More than that, each technology has its own qualities—there are several other technologies, such as SLS and STL, which may fit some design and fabrication challenges better.

We believe that the potential of 3D printing lies beyond the fabrication of a standard, or a slightly modified traditional instrument. It has potential for things that are not easily or even cannot be achieved in traditional fabrication techniques. For example, bending a metal tube (like in a horn or a trumpet) is not an easy task, but bending several tubes together, when these tubes are placed inside each other, is a far more difficult task. However, to print such a design is no more difficult

Fig. 9. An illustration of wind instrument parts—valves, springs, mouthpieces, and bell. All these parts have been printed and tested. This computer rendering was made using V-Ray software.

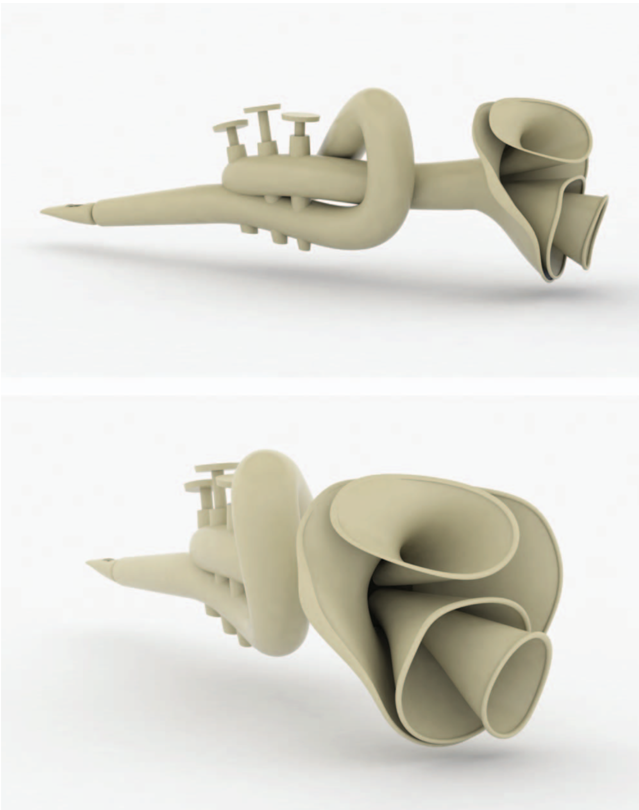

Fig. 10. An illustration of a conceptual, visionary trumpet. This computer rendering was made using V-Ray software.

than printing a single pipe. In Figure 10 a concept design for a trumpet is presented—a trumpet with multiple tubes of different radii. The valves' mechanisms can control which of the tubes contributes to the airflow. This is only one example of the potential that 3D printing technologies can add to the fabrication of digitally designed instruments, opening up new possibilities to visualize and simulate designs and rapidly fabricate them. Instruments that are made by 3D printing can be modified rapidly and easily, using the CAD tools. As such, costume designs are much more accessible than with traditional manufacturing, usually requiring specific tools, moulds, and machines for each design.

5. Conclusions and vision

In this paper the potential of digital fabrication—and especially 3D printing—as a fabrication technique for musical instruments was presented. The discussion was focused on wind instruments in general and the concert flute specifically, while evaluating two printing technologies. The motivation of this work is to inspire musicians and instrument makers, and to demonstrate the potential of 3D printing for the design and manufacturing of new instruments, which can lead to new acoustics, ergonomics and aesthetic solutions for future instruments.

While 3D printing technologies still have significant drawbacks—such as resolution, material quality, and stability—limiting their use for manufacturing (instead of prototyping)—we can easily envision how future digital fabrication technologies can play a major role in paving the way for new acoustic instrument designs. When the technology becomes more mature, digital design and fabrication tools could enable shapes and modification that cannot be achieved otherwise. Whether modifying an existing standard (for example, adding one more valve to a trumpet), or creating totally a new instrument, musical instrument designers can benefit greatly from digital fabrication technologies.

As in many other fields, the use of a CAD model prior to fabrication enables functional simulations and aesthetic ones, predicting the qualities of the final results. The use of a finite-element method (FEM) to simulate the acoustic behaviour of a vibrating object is not new to instrument design (Zoran, Welch, & Hunt, 2011b), determining the eigenmodes of resonators as part of their design process. In rendering—the process of visually simulating the look of the CAD model (see the rendered images presented in the paper)—we can test the aesthetic of a design, enjoying photorealistic quality. Using FEM and rendering prior to 3D printing, musicians and makers can enjoy a shortened design process, minimizing errors and determining the exact behaviour of a new instrument yet to be made.

We should not forget that 3D printing technologies, or any other novel fabrication technologies, cannot compete with the traditional ones in the process of fabricating traditional instruments. However, the new technologies have the potential to change instrument design, and to open a door for new acoustic experiments and musical possibilities. As such, digital instruments, acoustic 'traditional' instruments, and acoustic 'experimental' instruments can coexist, and can perhaps merge into hybrid instruments, integrating different qualities and different fabrication technologies.

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