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Using additive Manufacturing to Liberate Unplayable Instruments into the Musical World

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Abstract

Many ancient instruments belonging to important museum collections are classified as unplayable due to safety concerns or fragility. This article discusses an innovative method using additive manufacturing and acoustics to create replicas that match the original instrument not only in geometry, but also in sound - all without directly handling the original instrument. The method presented has the potential to liberate ancient instruments into the musical world, marking a new paradigm in museology and musicology. This article takes heavy inspiration from my research project in Engineering Science, titled 'Ancient aerophones: additive manufacturing of ancient musical instruments' which talks in much greater depth about the acoustic theory behind the article. For those interested I would be happy to share the full report.

Motivation

Ancient instruments can be rendered unplayable for a variety of reasons. Some pose a risk to the player's safety, while others are susceptible to damage from the player. The former case is often attributed to the presence of toxic pesticides. Historically, instruments (and other artefacts) were coated with pesticides as it was perceived as the only effective means of preventing damage from pests such as insects, rodents and mould [1]. However, as a result, these instruments are now unsafe to play. The latter occurs when an instrument is simply too fragile to be handled without risk of damaging it. This is especially true for aerophones (wind instruments) where the moisture introduced by a player's breath can have a destructive effect.

The ability to create and interact with replica musical instruments holds immense cultural and social significance. Live performances using replica instruments can be profoundly meaningful, particularly for members of the originating communities who may wish to reconnect with their heritage. Furthermore, the introduction of tactile exhibitions enables museums to modernise, enhancing their accessibility and fostering greater public engagement.

Background

Before we can delve into the discussion of creating replicas, it is helpful for us to consider some theory behind musical instruments. A musical note comprises a fundamental frequency and a series of higher harmonics, at integer multiples of the fundamental frequency. The pitch of a note is determined by the fundamental frequency, which in turn is determined almost exclusively by the instrument's geometry. The timbre of the note, which can be thought of as the colour of the sound, is determined by the composition of its higher harmonics. The composition of higher harmonics is also determined by the geometry, but is influenced by the acoustic, material, and surface properties of the instrument[1]. Academic literature suggests that acoustic properties[2] are the most significant in affecting an instrument's timbre after geometry, and we can use this to our advantage when producing replicas. [2]

From reading the abstract of this article, an obvious question arises: how can we know what the original instrument sounds like if we can't play it? This problem is addressed by building on conclusions from a previous research paper (Kirsch, 2020 [2]) which reached a significant conclusion: if two materials have comparable acoustic properties, the instruments manufactured from the respective materials will sound alike. Consequently, we don't need to play the original instrument, we simply need to determine the acoustic properties of the original material - a task that can be done non-intrusively. Then, we can manufacture a replica from an acoustically equivalent material to create a replica that closely resembles the sound of the original.[3]

To determine the acoustic properties of an instrument's material we can use a literature review. Museum catalogues, historical records and excavation reports all offer insights into the material properties. Subsequently, acoustic databases can be used to relate,

[1] This is a very brief overview. The field of acoustics is both incredibly broad and important in engineering. If you are more interested, the University of New South Wales, Sydney, has this great webpage: https://newt.phys.unsw.edu.au/jw/musFAQ.html#acoustics
[2] It should be noted that material and acoustic properties are intimately linked. Longitudinal and transverse sound speeds and acoustic impedance can all be expressed in terms of material properties, although this does assume that the material is isotropic, homogeneous and behaves linearly elastic.
[3] Specifically, we are interested in acoustic impedance, the measure of resistance to sound propagation through a material. An 'acoustically equivalent material' would be one with an acoustic impedance as close as possible to the original material.

albeit sometimes tenuously, the original material to an acoustically equivalent one. An example of this process is discussed below.

Next the manufacturing can begin. One question raised is: why use additive manufacturing instead of traditional craftsmanship methods? It could be argued that traditional manufacturing methods have the benefit of producing more authentic replicas. However, in instances where the craft is no longer practised or the specifics of the technique are unknown, traditional craftsmanship methods are not possible. Additionally, one of the key benefits of additive manufacturing is that print times are generally independent of the geometric complexity of the digital shape. For example, detailed engraving, textures, and patterns negligibly increase the print time. This characteristic is not true for traditional manufacturing techniques.

Case Study

The approach outlined above has been proven feasible for a small ceramic whistle (Figure 1) from the Pitt Rivers Museum, Oxford. The whistle was made in Peru in the Chancay period (between 1000 and 1476CE) [3]. Despite the museum catalogue offering little insight into the whistle's material [4], we can conduct a literature review to gather additional information.

Figure 1: Side view of the ceramic whistle from Peru, which dates to the Chancay period [4]

In Chancay civilisation clay was primarily sourced from local deposits, typically requiring preparation before use. Additives known as tempers were used to enhance their workability and firing behaviour. For highland clays, mica was added to increase plasticity, while for coastal clays ground-up sand or shell was added to reduce plasticity [5]. To achieve a dark-coloured finish, clays were fired in reduced oxygen environments, whereas, when a lighter finish was desired, a draft was used to create an oxygen-rich atmosphere [5]. Incomplete archaeological records obscure our understanding of pre-Columbian ceramic production, with questions remaining regarding the exact firing technology available at the time. However, we know that open fires or pit ovens were likely used [5] and while the firing temperatures were sufficient to vitrify the clay, they likely did not exceed 1000°C[1].

From this information we can make some broad comments. The reddish-brown appearance of the whistle, the constraints on firing temperatures, and soil composition in the Chancay region, all suggest the whistle's material is akin to modern red Terracotta[2]. Subsequently, we can use online literature to determine the acoustic properties of the terracotta[3]. Table 1 compares the properties of terracotta with a range of 3D printable materials. Notably, Zetamix, a filament made from a polymer binder mixed with porcelain powder (55% by volume, 75% by mass) [7], has an acoustic impedance of within 0.11% to that of Terracotta. Hence, building on the conclusions of Kirsch's research paper, we can label Zetamix as an acoustically equivalent material to Terracotta. Consequently, Zetamix is selected for additive manufacturing of our replicas.

Material	*Density (kg/m3)*	*Speed of Sound (m/s)*	*Acoustic Impedance (kRayl)*
Terracotta	1992.3	1484.9	2958.4
Zetamix	2554.6	1156.8	2955.2
PLA	1107.3	2191.5	2426.7
Resin	1167.7	1840.2	2148.9

Table 1: Acoustic properties of 3D printable materials [8][9].

[1] Literature on kiln designs, processes and firing schedules is scarce. However, Scott and Meyers [6] detail the firing of a kiln in the Batan Grande region (north Peru) from 400CE. Local wood was used as fuel and temperatures were recorded using thermocouples, reaching a maximum of 800°C. Of course, this kiln predates the Chancay era by approximately half a century. Due to the lack of documentation between 400 and 1000CE, we can only speculate on the improvements to furnaces in this period. Nonetheless, we assumed for this case study that temperatures achieved by Chancay furnaces remained below 1000°C.

[2] Of course, there are methods to obtain more exact information about the material of an ancient artefact. For example, using non-destructive methods such as X-ray Fluorescence (XRF), X-ray Diffraction (XRD) and Scanning Electron Microscopy with Energy-Dispersive X-ray Spectroscopy (SEM-EDS) gives us quantitative information about material composition.

[3] Some materials have more acoustic data online than others. For example, acoustic properties of metals have been comprehensively studied so data is plentiful, whereas ceramics are less well studied. This is a potential limitation of the project.

A 3D digital model of the original instrument can be achieved using computed tomography (CT)[1]. X-rays are transmitted through a slice of the sample, reaching a detector. By rotating the sample, a detailed cross-sectional image is generated. After this process is repeated incrementally along the sample's length, specialised software constructs the 2D images into a 3D digital model. Figure 2 illustrates a small subset of the cross-sectional images obtained from the CT scan of the original Peruvian whistle. Approximately two thousand slices were taken, separated by 22.344 microns. For simplicity, Figure 2 only shows seven. The resulting model is shown in Figure 3, with lighter regions indicating internal chambers.

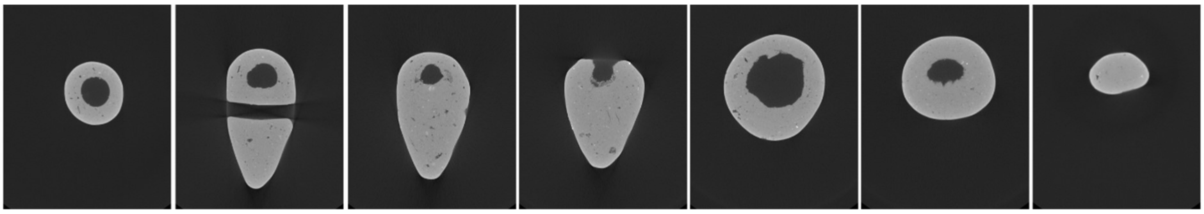

Figure 2: Cross-sectional images of the original Peruvian whistle created by the CT scan

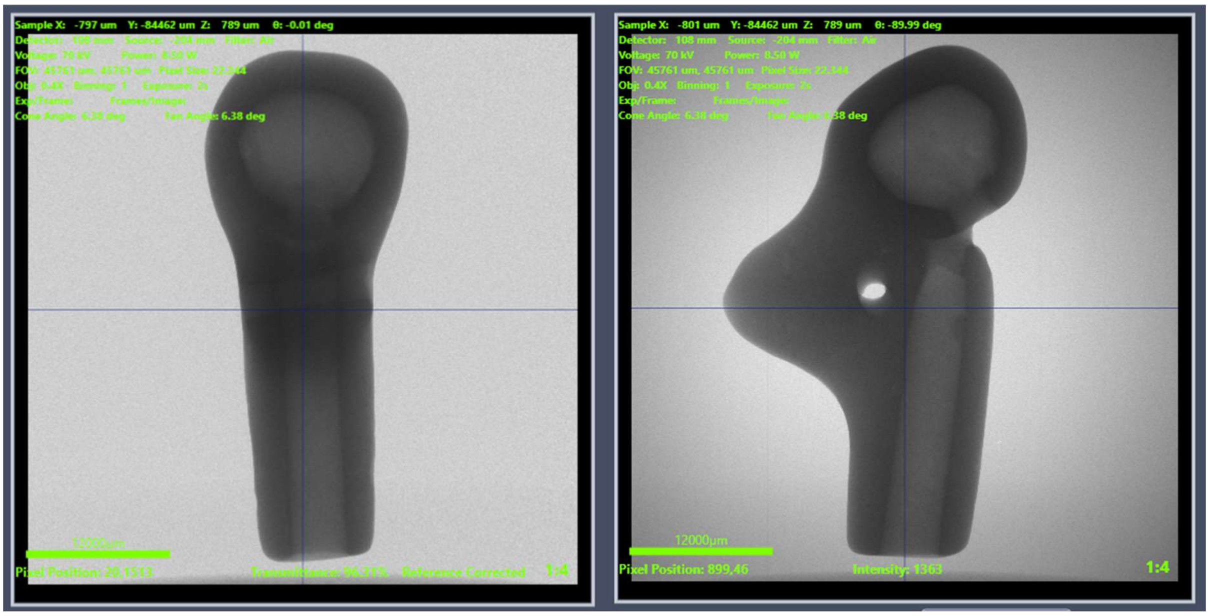

Figure 3: Display from the CT scan software showing the digital model of the original Peruvian whistle from the top and side view

[1] Use of a CT scanner is the largest logistical challenge to make this project accessible. Buying a micro-CT machine can cost around £300,000, however, some Universities offer use at an hourly rate of around £100 [10]. In our case, the Pitt Rivers Museum was able to use a CT scanner belonging to the University of Oxford free of charge.

Figure 4: Zetamix whistle

Once a model is obtained, we can begin 3D printing from our acoustically equivalent material. The two most widely used 3D printing methods are Fused Deposition Modelling (FDM) and Stereolithography (SLA). FDM involves extruding a filament through a heated nozzle and melting it, before depositing it onto the build platform to solidify. This is done layer by layer, with the location of the nozzle relative to the build platform being carefully controlled by computer software. In SLA, the build platform is submerged upside-down in a vat of resin. An ultra-violet laser is used to selectively cure the resin layer by layer, in a process referred to as photopolymerization. The benefit to this process is that it gives superior detail, and a smoother surface finish compared to FDM since the laser spot size is much finer than the FDM nozzle diameter and the layers are printed thinner. However, FDM is typically easier to use, with a shorter print time and a wider variety of available materials.

In this case, Zetamix is printed by FDM, before undergoing a multi-stage post-printing process involving debinding and sintering. Figure 4 shows the 3D printed Zetamix whistle after post-processing. With a physical model produced, we can blow the whistle and hear the note it produces. Since we have established that Zetamix is an acoustically equivalent material to Terracotta, we can infer that the sound produced from the whistle closely matches that of the original[1].

Limitations

There are a few limitations of this process. Firstly, the size of the instrument is constrained to the dimensions of your 3D printer bed. We can't print trumpets or tubas to scale without an incredibly large 3D printer. Secondly, the ease of manufacturing varies greatly between different print materials. Historically, ceramics and metals proved too difficult to integrate with 3D printing methods and only in recent years has their use become feasible. However, there are still limitations in the range of products available to a consumer and challenges relating to specialised apparatus[2]. Finally, we

[1] We can go further, and record the sound produced and analyse the frequency spectra of the note. This gives us insights into the natural frequency, and composition of higher harmonics. We can then compare these properties against whistles printed from other materials, describing the difference in sound quantitatively.

[2] 3D printing of ceramics (including Zetamix) requires a high temperature furnace for thermal debinding of the polymer matrix. Printing of metals requires specialised Direct Metal Laser Sintering 3D printers.

must consider that ancient instruments can hold great importance that extends beyond their physical form. For example, the religious, ceremonial and spiritual roles an instrument played contribute significantly to its intangible cultural and social value. While this can mean creating and interacting with replica instruments can be immensely valuable, it also can raise questions regarding cultural appropriation, ownership, and intellectual property. Consequently, the replication process outlined in this article should be completed in a culturally sensitive and morally responsible manner.

Conclusion

In conclusion, the use of additive manufacturing to replicate ancient musical instruments offers an innovative solution to the challenge of preserving and interacting with unplayable artefacts. This method opens new opportunities for museum collections, allowing for safer handling and public engagement through tactile exhibitions and live performances. Furthermore, there is significant potential for future collaborative work with composers and musicians. A long-term objective could involve orchestrating a musical performance featuring exclusively additive-manufactured replica instruments, offering profound cultural and educational value. Such a performance would immerse audiences in ancient music, history, and culture in a way that traditional displays cannot. Moreover, this method can provide composers with access to unique sounds that could inspire new compositions. The integration of additive manufacturing in the fields of museology and musicology represents a transformative step forward, merging engineering, history, and art in a way that fosters deeper connections with our cultural heritage.

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