Considerations for the design of composite 3D printed ‘intermediate level’ trumpets

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Using 3D printing techniques, it is now possible to create almost any small to medium object including brasswind instruments. However, creating a competitive brasswind instrument requires a different approach to conventional 3D printing - demanding specialised printing techniques which, up to now, have only been applied to the prototyping stage. This paper is a review of the considerations in the design process for a composite Bb trumpet aimed at the intermediate level player. The trumpet is the next step up from introductory level instruments such as the pTrumpet or Tromba. As such, it must be comparable to brass equivalents available from manufacturers such as Vincent Bach, Getzen, and Yamaha. The acceptance of such an instrument is as important as the design therefore composite instruments would need to have ‘added value’ compared to their brass counterparts if they are to be successful in the marketplace. Many professional trumpet players such as Alison Balsom, Mike Lovatt, Sam Ritchie and Charlie Peterson have already endorsed the plastic trumpet for student use. To introduce an intermediate or professional composite instrument may therefore be considered appropriate at this time. Two hybrid prototype Bb intermediate level trumpets are fabricated using 3D printing techniques and analysed using different bell types. Consideration of timbre, ease of playing (ergonomics and fatigue), leadpipe and bell design is discussed. The application of different 3D printing technologies is also considered. The resultant trumpets are shown to be comparable to typical mid-range brass equivalents.

3D printing. 3D printed trumpet. Composite materials. Timbre. Acoustic impedance.

1. INTRODUCTION

The evolution of the modern day trumpet has been relatively slow with few innovations taking place since the early designs in the 1920’s and 1930’s by Besson (Wallace 2011). However, the most recent innovation has been the development of the composite material or ‘plastic’ trumpet in 2014 with the introduction of the pTrumpet (2014), Tromba trumpet (2014) and Tiger/Playlight (2014). These instruments have been designed for use by young learners; being light and almost indestructible if dropped. This is in part due to the use of ABS as part of the manufacturing process and part design. International sales of pTrumpets have been high with 50,000 units having been produced (Warwick Music Group 2017). Several years has now passed since the introduction of these instruments and learners are at a stage where they are progressing to step-up instruments. However, there are currently no intermediate level composite instruments available. This paper considers the development and construction of prototypes for new step-up instruments based upon the success of the pTrumpet and Tromba using 3D printing techniques.

2. PRINTING TECHNOLOGIES AND MATERIALS FOR INSTRUMENTS

Composite materials for the manufacture of musical instruments has been used for many decades. Maccaferri patented a plastic woodwind reed in 1941 followed by guitars in the 1950s and a violin in the late 1980’s (Maccaferri 1988). Nuvo introduced plastic flutes and recorders in 2007 as a serious alternative to traditional woodwind instruments for young learners and the pBone and pTrumpet were introduced in 2011 and 2014 respectively as alternatives to brass instruments. Digital designs of instruments have been available over the last several years with 3D printable downloads available from sites such as Thingyverse and TechRepublic. Recorders, trumpets, and guitars are available.

However, all are of low resolution printing and are not for the serious player. Other specialist instruments have been produced by artists and manufacturers such as Olaf Diegel who has used metal 3D printing techniques (Chua 2014) and Monad (MONAD Studio 2017) who have manufactured esoteric 'cellos and piezoelectric violins.

Zoran (2011) explored the possibilities of creating instruments using a 3-dimensional printer with respect to the flute using fused deposition modelling (FDM) technology which builds up consecutive layers of thin plastic until the digital model is realised, and Polyjet technology. This uses acrylate-based photopolymers which are cured using UV light. He found that a 'common problem' with the FDM technology is a propensity for cracking to form between layers and that small parts had to be replaced with metal such as springs and pads.

The material used is Acrylonitrile Butadiene Styrene (ABS), notable for its strength and ubiquity in 3D fabrication (3D Printing Industry, 2016). Other popular composites include Polyamide, Alumide and Polylactic Acid (PLA). PLA tends to brittle, inflexible and prone to breaking when bent (Grieser, 2016) so is unsuitable for instrument printing.

Polyamide is a strong, flexible and durable plastic used in the sintering process or through the FDM method. These qualities tally with the requirements for instruments; being strong and durable, it will likely prove resistant to deformation, thus conducting resonance better. Its application in the sintering process is advantageous as it would benefit from a higher resolution and wouldn't suffer the cracking between layers highlighted by Zoran.

Table 1: *Physical properties of prospective materials (values taken from MakeItFrom.com, 2006)*

Material	Density (g/cm³)	Young's Modulus (GPa)	Tensile Strength (MPa)
Yellow Brass (Copper/Zinc Alloy)	8.3	110	310-650
Acrylonitrile Butadiene Styrene (ABS)	1-1.4	2-2.6	37-110
Alumide	1.35 ± 0.05	3.8	48
Polyamide	1	0.4-1.3	25-51
Polylactic Acid (PLA)	1.3	3.5	50

Polyamide can also be combined with powdered aluminium to produce Alumide – a metal composite used in sintering. This is an attractive option as the inclusion of aluminium could enable a closer replication of the qualities found in yellow brass whilst still providing the same logistical flexibilities of plastics. Cosmetically, it also offers a 'metallic appearance' (Stirling, 2008)

Here, it can be seen Polyamide, and to some extent Polylatic Acid, are inappropriate. However, Alumide compares favourably with ABS – a material which has had relative success in low-scale instrument manufacture. The density is in the upper bound of that of ABS and the Young's Modulus of Alumide exceeds it considerably. The tensile strength doesn't compare as favourably but it is questionable how relevant this is as the instrument should not come under extreme stress.

Since Zoran's paper other methods of 3D printing have been developed which overcomes many of the issues he describes. A process known as selective laser sintering (SLS) uses a laser to sinter powdered material as defined by a 3D model and binds it together to make a solid structure. This is useful for rapid prototyping and low volume production of larger items. High resolutions of finish are attainable and due to the choice of materials that may be used, is appropriate for musical instrument development.

A further, more recent method of rapid prototyping is Continuous Liquid Interface Production (CLIP), capable of creating smooth walls, in which the material is equivalent to injection moulded parts (Carbon3d).

The choice of technology requires a solid structure with a high resolution finish. Both SLS and CLIP methodologies are appropriate. However, as CLIP is relatively new, the opportunities for manufacture are limited (availability and cost) and therefore SLS, being an established method, is deemed most appropriate for developmental work on prototypes.

Table 2: *Physical properties of VEROPUREWHITE RGD837 (values taken from Polyjet Materials Data sheet 2016)*

Material	Density (g/cm³)	Flexural Modulus (MPa)	Tensile Strength (MPa)
RGD837	1.17-1.18	2200-3200	75-110

For the manufacture of the trumpets presented in this paper, a rigid opaque material with similar specifications as ABS has been chosen. As the final instrument is to be mass produced using injection moulding methods in ABS it is important to simulate it in the prototyping stage. VEROPUREWHITE RGD837 (stratasys©) has been chosen as this has been used in previous prototyping solutions by Warwick Music Group. Table 2 details the physical properties.

3. DESIGN CONSIDERATIONS

The modern-day trumpet has many factors contributing to its sonic profile which, whilst all affect the 'signature' of the instrument, some do to a greater or lesser extent. These must be taken into consideration within the development process.

3.1 Timbre and the bell

Kausel (2007) and Buick *et al* (2002) concluded the greatest influence on sound was the diameter and graduation of the bore. Others believe it lies in the dimensions of the mouthpiece (Morrison, 2013). Zicari *et al* (2013) investigated the effects of altering the internal mouthpiece cup contours ('U' and 'V' shapes) and varying the throat junction (round and sharp). Results for this study, whilst well documented, seem a little inconclusive.

However, the overwhelming body of research found seems to point to the bell of the trumpet being the biggest dictator of timbre (Buick, 2002 and Gibson, 2016). More specifically, the vibrations of the bell wall (Moore, 2003 and Chatziioannou, 2012). Moore noted that the relative power of the fundamental can be shifted by more than 3dB 'when the vibrations in the bell section are dampened.' He went on to suggest it is 'almost universally believed' that the material and thickness of the trumpet bell 'does indeed have a large effect on the acoustic spectrum'. There is opposition to this belief with Smith (1978) stating that changing the material of the bell has 'no effect' on the sound. Moore's stance does seem to be the more popular, however, with the likes of Nief (2008) offering concurrent, albeit muddled, findings supporting the connection between wall vibrations and timbre. Kausel (2010) offered more robust support, claiming that, whilst the aetiology of the bell's impact is largely unknown, the findings of their research indicate that the 'majority of audible effects' are a direct result of the 'presence of strain oscillations' in the bell and their interaction with the air column of the instrument.

Based on Moore's research, if the pattern of vibrations of the plastic trumpet can match that of the brass then the timbres should also align.

Smith notably disagreed with Moore and Kausel over the effect of different materials; his argument was that thickness was a greater influence. He stated 'players and listeners cannot distinguish between a trumpet with a fibreglass bell and a brass bell' (Smith, 1978). In this experiment, however, like for like thicknesses were not compared. Had the fibreglass and brass instruments been of the same thickness, there may have been a perceivable difference - but by altering the thickness, the timbres were matched.

This leads to the belief it is an interactionist relationship between the two; if the material is to be changed, then so must the thickness so as to match the rigidity and absorption of vibrations. Schilke (nd) described this as the material's resilience to vibration and ability to withstand deformation – also referred to as the Young's Modulus. Plastic is less dense so, to withstand deformation equally, the strength comes from added thickness. It dictates that if the timbre is to be equalled, then the material cannot be changed without also changing the thickness accordingly.

The bell therefore dictates the timbre of the instrument due to its acoustic and material properties. Rather than redesign the flare of the bell a choice of existing bell flares has been considered based upon professional instruments; Vincent Bach Stradivarius 180ml 37 and a lesser known George Schlub design based upon the Yamaha intermediate level 'Bobby Shrew' trumpets. These should sound similar to their brass counterparts if material thickness is taken into account.

3.2 Leadpipe design

The leadpipe together with the bell influences the resonances of the air column in the instrument due to the bore profile (Buick 2002). Smith explains that the resonances that make up the timbre of the instrument are influenced by the conical bore of the lead pipe and bell; in turn affecting the air column allowing it either to be radiated or reflected back within the instrument. A small bell reflects more of the energy within the air column thereby supporting the resonance. The shape therefore determines how much is reflected back to the player. The leadpipe, in turn, is used to reflect the wave back to the bell. A smaller leadpipe would appear to help support the resonances but the player must also be able to input the vibrational energy from the lips and so a compromise must be made else the player fatigues. This would suggest that there is an infinite combination of bells and leadpipes although, in reality, there are only a small number of bell profiles available due to the high cost of the manufacturing tools. As such, leadpipes vary between manufacturers. Smith and Watkins (Leadpipes and Bells, nd) produce interchangeable lead pipes of differing sizes to suit players based on three basic profiles as examples. An issue that arises from the manufacture of a lead pipe is the accuracy of the tolerance of manufacture required. Buick demonstrated that a 0.1 mm change in the bore shape at the smaller end would have a significant effect on the sound produced but the accuracy of manufacture showed that the differences were smaller than 0.03 mm. Whether this negatively influenced the tone was not discussed.

Petiot (2005) demonstrated that the harmonic spectrum of a note is due to the shape of the instrument (leadpipe and bell) rather than the way it is played. This reaffirms the notion that an instrument has a tone 'signature' and, with appropriate design, can emulate timbre characteristics.

3.3 Valve block and valves

Valves are used to divert the flow of air through additional pipes called the 1st, 2nd and 3rd valve slides. They need to move freely without any restrictions. Materials are normally chosen depending on the level of instrument. Typically student models use Nickel plating which is plated onto the valve and depending on the quality of manufacture may be prone to flaking. Monel is a solid nickel copper alloy which is resistant to corrosion and considered to be hard-wearing but can suffer from an electrolytic reaction between piston and casing with brass leaching onto the valve from the valve block. The most popular choice for intermediate and professional trumpets is stainless steel as this is similar in hardness to Monel without any of these reaction issues. According to Getzen (2006) the surface finish and build quality are most important in valve construction. The surface corrosion and or finish can damage the softer valve casings so reduce the compression of the instrument but this depends on how well the valves are looked after (oiled and cleaned). In general, manufacturers agree that whichever material is used the valve will work so long as it is maintained.

In the pTrumpet the valve block and valves were made of ABS with only the springs being made of metal. Issues of temperature variation have had a limited impact on the functionality of the valves with sticking being an issue on occasion. However, due to the behaviour of plastics creating friction when rubbing against each other, fast action is not possible therefore alternatives solutions are required.

4. DESIGN AND MANUFACTURE

The trumpet design is based on a hybrid model, utilising both plastic and metal materials. This provides an opportunity to make the instrument more robust and perform similarly to traditional brass equivalents.

4.1 Design concepts

Two trumpets are fabricated to enable investigation of the influence on timbre using different bells. Both designs comprise the attributes of the pTrumpet; a Vincent Bach #25-O leadpipe which is stated as free-blowing with a 0.349" venturi. As with the early Vincent Bach trumpets there is no stepped bore or reverse lead pipe. The bore is a standard 0.460 inch medium large design. Two bell designs are used; a Vincent Bach model 37 and George Schlub, similar to the Yamaha 4335 with a 4.5 inch and 5 inch diameter flare respectively (labelled as 4.5H and 5H). The bells are 2mm thick which is the maximum reliable thickness applicable to injection moulding for manufacturing purposes.

In plastic, an area susceptible to large environmental variation is the valve block and piston assembly. This is the area in the system where air is most likely to exit. To minimize this, a high-tolerance metal solution can be employed. Looking towards commonly used materials in traditional manufacture stainless steel and brass is selected and using laser cutting technology, as used in medical implement manufacture, sleeves and liners made to the highest levels of tolerance. Plastic inserts are fabricated to mount the sleeves, springs and buttons allowing for a strong but light solution to construction.

Figure 1: *Hybrid 3D printed valve using stainless steel sleeve*

Water keys are aluminium with stainless steel springs and have a shaped 'cork' to maintain the smoothness of the inside bore of the slides.

The leadpipe is modified to carry a metal mouthpiece using a brass receiver. This allows metal mouthpieces to be used with the trumpet and provides a gap between mouthpiece and leadpipe of approximately 1.5 to 3.00 mm depending on size and wear of the mouthpiece. The influence of the gap is debatable with some manufacturers stating the need for it with regards to ease of playability (Warbuton-usa.com, nd). However, the use of a metal receiver negates the possible effects of swaging the plastic and having a poor fit of the mouthpiece.

Both the 1st and 3rd valve slides are adjustable using finger rings as found on most modern-day trumpets. Due to the complexity of manufacture the rings are not adjustable although this is similar to many top end professional instruments such as the Schilke HD, X and B series as examples.

4.2 Manufacturing

The instruments have been produced in China using SLA technology on a UnionTech Lite450 SLA 3D printer with an accuracy of +/- 0.1 mm, +/- 0.1%.

The material used has been discussed in section 2 with its properties tabulated in table 2. The whole body of the instrument is electroplated with a gold lacquer to give a final finish to the instrument. Appropriate toxicity testing of the plating materials used was undertaken to ensure safety of users and approvals by the SGS obtained.

An example of the final trumpet is shown in figures 2 and 3.

Figure 2: *SLS printed Bb trumpet electroplated in gold lacquer (4.5H)*

Figure 3: *Component parts of the 3D printed trumpet*

5. EXPERIMENTAL MEASUREMENTS

The resulting trumpets are empirically tested rather than modelled as they are based on existing brass instruments that are known to give an accepted timbre and playability to the musician. Five musicians performed a chromatic scale in an acoustically treated room over the range of the instrument (G3 to C6, Bb pitch). A test microphone is placed in the near field; a distance of 1 metre from the bell.

Two of the musicians are professional freelance players with many years of experience, two are semi-professional (author) and one an amateur (second author).

The chromatic scale is repeated three times at forte, once at piano and once at fortissimo.

This is performed for the two composite test instruments, and two comparable brass trumpets; an intermediate level Yamaha 4335, and a professional level Vincent Bach 180ml 37.

They are recorded with a DPA 4090 omnidirectional microphone with maximally flat response into an Audient ID14 preamplifier unit and recorded at 24 bit, 48 kHz using Logic Pro x software.

Tonality analysis is undertaken using MIRtoolbox using a long term average spectrum (LTAS). All attacks and delays are removed from each sample accounting for pitch deviation in these stages of the note.

The spectral envelope of the LTAS is plotted and relative gradient changes are observed. Subjective comments regarding the playability of the instruments were also noted. Tuning of each note is closely monitored.

6. RESULTS AND DISCUSSION

The results presented are the spectral envelopes (peak values) of the harmonics produced for the brass and associated composite trumpet (Bach 37 vs 4.5H, Yamaha 4335 vs 5H). This indicates whether there is a similarity in signature between the instruments. Notes C4 and G4 are represented as these are open notes – the valve slides and additional length tubing will not influence the measurements. Comparisons of timbre across different players and instruments are also presented as an indication of correlation regardless of player; countering, at least partially, the subjective nature of human involvement.

6.1 Timbre

The spectral envelope of G4 is presented in Figure 4 for player MP with the note represented twice at forte. Both the Bach and the composite equivalent, 4.5H are shown. The patterns indicate a similarity with the exception of the harmonics at approximately 2000Hz. Here we see a reduction in the overtones in the composite instrument. Figure 5 shows an almost identical pattern for C4. Similar trends were observed for other notes in many cases. Figure 6 again demonstrates similar attributes for player JS.

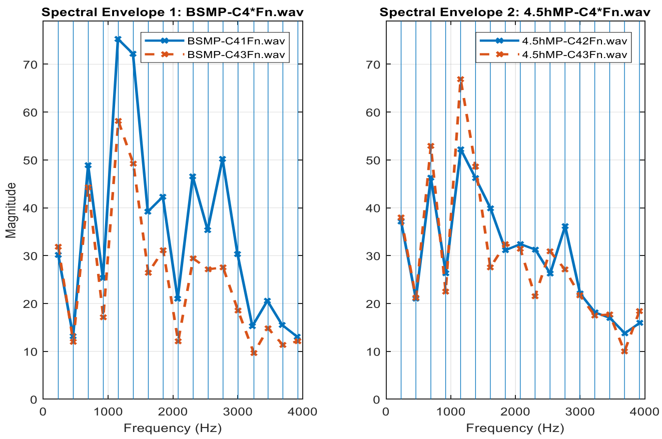

Figure 4: *C4 spectral envelope for equivalent brass and composite instruments, MP: small bell*

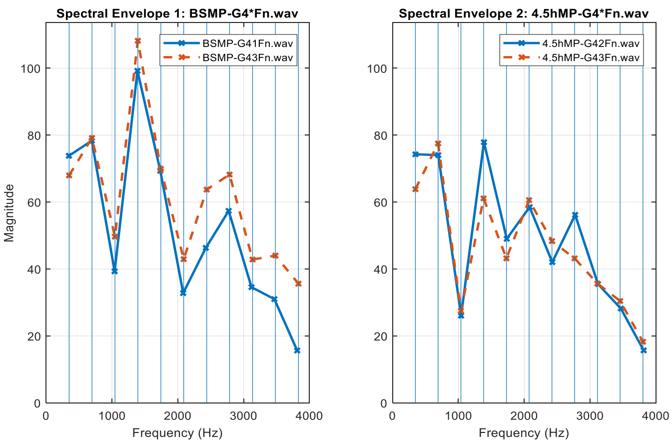

Figure 5: *G4 spectral envelope for equivalent brass and composite instruments, MP: small bell*

Comparison between the Yamaha 4335 and the composite 5H again shows similarities in the timbre as shown in Figure 7 and 8 for player MP. Again a similar pattern was observed for other notes. Figure 9 shows G4 for player DG. A similar pattern to G4 MP can be observed. This suggests that the instrument may have a greater influence on the timbre rather than the player or mouthpiece, as suggested by Petoit.

In terms of actual perceived sound, observers noted a slight difference in the timbre with the composite trumpets having less 'edge' or a 'more rounded sound' which is indicative of the harmonic discrepancy just above and below the 2000 Hz region.

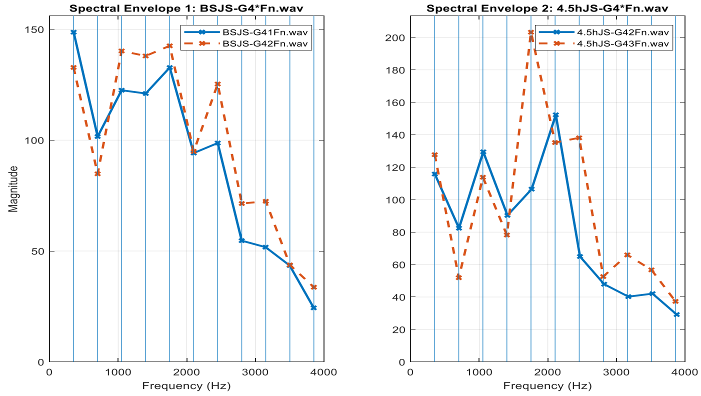

Figure 6: *G4 spectral envelope for equivalent brass and composite instruments JS*

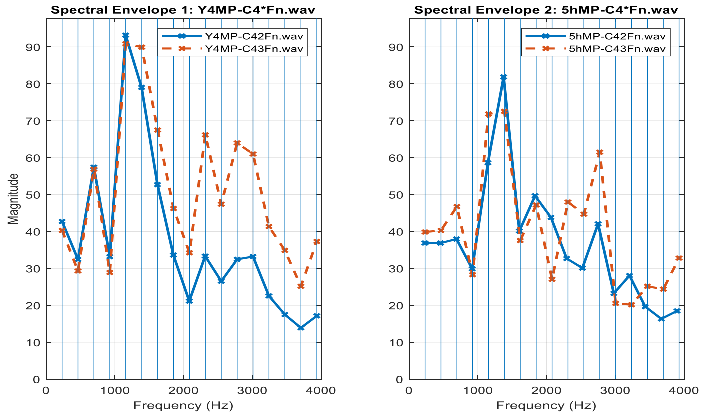

Figure 7: *C4 spectral envelope for equivalent brass and composite instruments MP large bell*

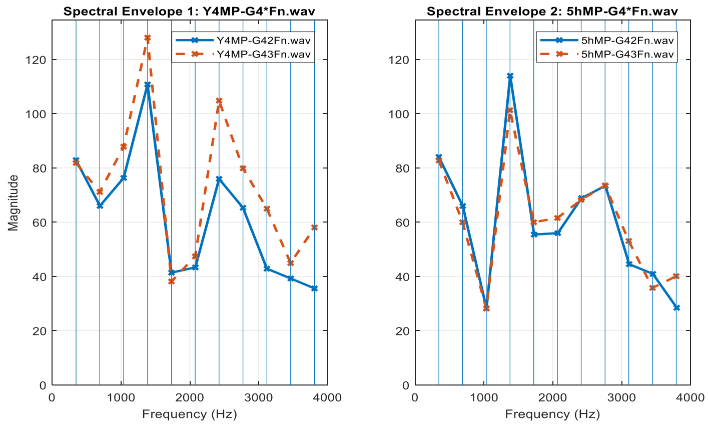

Figure 8: *G4 spectral envelope for equivalent brass and composite instruments MP large bell*

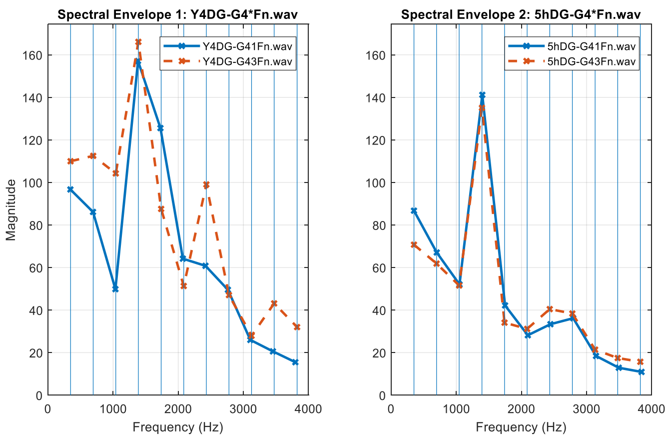

Figure 9: *G4 spectral envelope for equivalent brass and composite instruments DG large bell*

6.2 Subjective feedback

Professional and amateur players were asked to play and comment on the instruments to obtain a subjective view of their playability and timbre. All players said how well the instruments played both in terms of sound and intonation. Most notable was the finding that those accustomed to playing a Bach favoured the 4.5H whilst those used to Yamahas or similar, larger belled instruments favoured the 5-inch model. This strongly aligns with early predictions of the existence of 'families' of timbre and that similar bells will produce a similar sound.

7. CONCLUSION

The application of composite materials in the production of prototype intermediate level trumpets has been shown to be possible. The use of SLA 3D printing techniques has enabled two trumpets to be manufactured both of which have been empirically tested. Intonation and timbre have been shown to be similar. Musicians who normally played on the Bach family of trumpets preferred the equivalent composite instrument whilst those who played on Yamahas or big belled instruments preferred the larger of the two. Both trumpets performed at a level similar or better than equivalent brass instruments paving the way for injection moulded mass produced instruments to be manufactured. Due to the printing methodology employed it is now possible to alter or modify the instrument design and enable customisation of a trumpet based on specific user parameters. Further analysis of the 'signature' of an instrument type will need to be conducted if replicas of known types are to be produced. Using newer 3D printing technologies such as CLIP will enable faster production of these one-off instruments. However, particular components such as the valves will still need to be manufactured from traditional materials if such instruments are to be accepted by the music industry.

8. ACKNOWLEDGEMENTS

We would like to thank John Shepard, Anthony Thompson and Colin Farlow for their time and effort in playing chromatic scales on so many instruments for so many times and Warwick Music Group for providing the instruments and manufacture of the composite trumpets.

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