Viability Of Additive Manufacturing For Use In Brass Instruments

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Part 1 - Personal Statement

My research topic is how additive manufacturing, particularly 3D printing, benefits the construction of musical instruments. Additive manufacturing machines and processes are becoming cheaper, more efficient, and more precise over the past decade, stemming from the business market into the consumer market. Cheap and functional 3D printers can be bought for less than $200, and more and more schools, shops, businesses, and makerspaces are buying them more than ever before. While musical instruments largely follow this same trend of becoming less expensive as manufacturing processes become more efficient, specific instruments fall behind due to their low demand and complexity, such as the tuba. In comparison between trumpet and tuba, a beginner trumpet costs as low as $100, while a beginner tuba costs more than 10 times that amount. This disparity creates a barrier to entry for those musicians who can not afford to buy their own instrument, further discouraging them from pursuing music in their lives.

My hope is that this research can be used to propose a solution to the aforementioned problem and potentially inspire those interested in both studying music and learning additive manufacturing, all while satisfying a great ambition of mine to construct a cheap, functioning plastic tuba. This research is a convergence of my two greatest passions, music and engineering.

At a young age, playing with LEGOs was commonplace. The number of possible arrangements for a bucket of LEGO bricks is endless, and thus, plenty of hours were spent creating many of those arrangements. Of my own volition, I isolated myself in my room for hours on end with an idea in mind, tirelessly manipulating the LEGO bricks with the hope of witnessing the idea become a reality. The tactility of the blocks gave me more energy, and once a less than optimal product arose after build, my only solution was to disassemble, assess its shortcomings, and strive to create something better. Experiences like these consumed the ample time one has at childhood, and it was my first glance into engineering.

Past those childhood days was the widespread use of YouTube, a platform to share videos with people worldwide who had an internet connection. It was through this platform that I discovered additive manufacturing in its most basic form: FDM 3D printing. The concept of a 3D printer fascinated me. Similar to a common ink printer, a fused deposition modelling (FDM) 3D printer extrudes heated plastic filament onto a surface, but instead continually builds upon the previous layer to form a tangible object. In late May of 2017, I gained access to a 3D printer and using it revolutionized my life and the way I thought about fixing problems. My first functional print was a bracket to guide the motion of a sliding closet door. Although designed and printed rather quickly, it successfully replaced its predecessor, which finally broke after years of use, and reminded me of the insatiable passion from childhood of building. Once the sliding door slid again, the revelation of the inherent flexibility and capabilities of additive manufacturing came to me and has driven me forward since.

Music, unlike engineering, was not a defining aspect of my life when I was young and I deeply despised listening to it. Watching my brother's piano recitals was the most sleep-inducing task when I was young, and during the recitals I always looked for something more worth my time to spare me from the "torture" of listening. These dreaded recitals marred the name of music, and not rightfully so, deterring any advances of mine toward loving music.

However, much to my dismay in fifth grade, my parents forced learning an instrument upon me. To spite them, I chose the unlikely xylophone as my instrument, and never have I once regretted making that decision with poor motives. Music provided me a family of like-minded musicians to connect to, concerts to attend and truly appreciate the effort of playing a show, and the better understanding of music in what it is fundamentally and all of its nuances. Learning music flipped the developed preconception into another loving passion.

In the fall of sophomore year, I began learning how to play the tuba. Contrary to mallet percussion, learning tuba was difficult initially, as little sound was produced in the long practice sessions, but as time progressed and more time was spent practicing, I began to enjoy and love the tuba. Once the tone of the tuba fell into place, the warming low tones that resonated throughout the room out of its horn made me love the instrument even more.

I am extremely fortunate to be able to continue with my passions without much strife. However, there are people who are not nearly as fortunate, and struggle with paving their road through this world. Music can motivate them to persevere and keep moving forward, and the last thing they should worry about is the barrier to entry for playing a desired musical instrument. Everyone should have access to the means to create music that they admire and love, and especially with newer technologies such as additive manufacturing arising, the cost should not factor into one's decision whether to pursue music or not. Those beliefs drive this research.

In particular, this research focuses on decreasing cost and inaccessibility of musical instruments using modern fabrication techniques. The expected course of this research is to investigate this problem using 3D printing and common off-the-shelf parts to hopefully culminate in fabricating a functional tuba while monitoring and minimizing the expenses. Taking into account the final product of the research, the driving research question is how the cost of brass instruments can be decreased using 3D printing to create parts.

Part 2 - Review of Literature

Additive manufacturing is a process where a machine gradually deposits material to an object such as to build a three-dimensional object layer by layer. This is more commonly referred to as 3D printing. There is huge potential in additive manufacturing due to the inherent traits of manufacturing layer by layer; a variety of complex, customizable objects can be fabricated easily and cheaply, allowing far more versatility than more traditional manufacturing processes such as injection molding. In its conception and early stages, additive manufacturing was an exclusive prototyping process, barricaded from the majority of people by its staggering costs and size of machinery. However, as these processes have become more efficient, refined, and inexpensive, the lure of its immense capabilities has seeped into the prosumer and consumer markets. As demand for 3D printing has increased, economies of scale have lowered the entry cost into the 3D printing so much that functional entry level 3D printers can be purchased for less than $200.

Many uncommon musical instruments, however, are not affected by economies of scale due to their low demand, resultantly being priced at extraordinarily expensive prices. This poses a great problem to aspiring musicians that are unable to afford such an instrument, and even more so for ones that choose to pursue a rare instrument. Furthermore, the musician may struggle to buy an intermediate instrument after purchasing such an expensive beginning instrument, hindering their capabilities in producing music. For tuba players in particular, a beginner level horn costs over $1000 and most only have three valves. As the player improves, a fourth valve is highly recommended to allow the player to fully unlock the contrabass range. If implemented successfully, additive manufacturing has the capability to revolutionize the beginner musical instrument market by significantly decreasing the cost of less common instruments, thus increasing accessibility and permitting more youth to play music.

This literature review discusses the feasibility of constructing a musical instrument augmented using additive manufacturing. Many studies have demonstrated promise for the use of additive manufacturing in constructing musical instruments. However, while some sources claim that there is potential, they state that their experiments were unsuccessful because the additive manufacturing industry had not developed enough. These specific studies were conducted rather early in the history of 3D printing, long before the entry of 3D printing into the consumer market.

Brass Instruments

<u>Material</u>

The various materials that comprise the numerous parts of a brass instrument have an effect on its sound, although the effect and degree of effect will be different depending on the material. Zappas of the Journal of Minerals, Metals, and Materials reports that the case for materials varies for every instrument. A violin made out of brass and a brass instrument made out of wood would not sound pleasant. However, Zappas' first source, Gregor Widholm of the University of Music and Performing Arts in Vienna, conducted an experiment using 7 flutes made with different metals from the same manufacturer and 7 professional musicians to play each instrument. He found that the sound of each flute had no differences compared to one another. Especially at professional levels of playing, the differences in sound can accommodated by the instrumentalists themselves. Furthermore, Zappas also puts forth a study by Richard Smith, who has a Ph.D. in acoustics and conducted a study on trombone bell materials and thicknesses, testing the different trombones on professional trombone players. The study showed that the trombone players could not distinguish between any of the trombones, despite the differences in vibration between separate trombones. However, Smith notes that the “internal shape is important to the sound, bell shape is important, and the lead pipes are important”, but not the material of the instrument. Smith, as a result, works with brass because it is the most malleable and easy to physically manipulate into an instrument.

On the contrary, Yamaha speaks about tubas with regard to their materials and surface finishes. They say that the materials that make up an instrument will have a slight effect on the sound of the instrument because the material of the instrument affects the way the air vibrates in the horn. Brass is typical of these instruments because it is not as corrosive as other metals and it is highly malleable. Brass is made of a copper and zinc alloy, with gold brass made of 85% copper and 15% zinc and yellow brass made of 70% copper and 30% zinc. Gold brass makes the instrument sound more rich and full, while yellow brass makes the instrument more bright and well-toned. Alongside the material of the horn, the surface finish does also have a slight effect on the timbre of the instrument, with a clear lacquer coating making the horn sound more solid and dark and project more when playing at forte dynamics. Silver plating, on the other hand, makes the instrument sound softer and brighter.

To add more confusion, recently plastic brass instruments have entered the consumer market, such as Cool Winds. Players Music shows a catalog of such instruments, which are all brass instruments that are made from ABS plastic. The prices of these instruments are rather cheap compared to similar brass instruments due to their plastic construction, although they boast metal valves. Anderson, who does play tuba and serves as an elementary school teacher, created a compilation of his thoughts on the Cool Wind tuba. When he first heard of the tuba, he thought he would never purchase one and said that it might be a good experiment, but never fully considered buying one. He bought his plastic tuba because it was a demonstration unit and the price had been lowered to a reasonable amount. It was not in working condition initially, but he repaired the leaks by sealing them with rubber adhesive and then the tuba worked surprisingly well. He documents that valves springs are strong and not fitting for beginning students. Also, he mentions the valve's construction, particularly the use of a brass sleeve inside of the valve housing and an aluminum valve. These valves were also easier to clean than the valves on his brass tubas. The tuba is also extremely light, being able to be held by one hand. As far as the playability of the tuba, it was not particularly hard to play, but his brass tubas were significantly easier to play than this tuba and the pedal range was shoddy. More muscle had to be used to sufficiently control the tone of this tuba as opposed to his Miraphone but, in the end, it still functions as a tuba. The consensus appears to be that brass instruments constructed out of brass are still superior to other materials, although other materials can still perform competently.

Bell

The bell is the flaring section of tubing at the end of a brass instrument. This section of tubing serves to refine the input buzzing from the mouthpiece. Firstly, the bell pitches up the notes in the lower harmonics of the instrument proportionately to their distance away from the approximate harmonic center of the instrument. Many people, on tuba player forums such as TubeNet, refer to this phenomenon as the bell effect. The pitching up of notes also provides the instrument with a low, fundamental note called the pedal note that cannot be present in cylindrical pipes. Secondly, the bell permits the sound of the instrument to project more than the sound of a cylindrical pipe, with the upper harmonics radiating more than the lower. The drawback to this boost of upper harmonics is that the notes of the upper harmonics are particularly susceptible to pitch bending, where the frequency of the harmonic is less defined and can raised or lowered easily.

The Hyperphysics website, created by the Department of Physics and Astronomy at Georgia State University, states that the bell forces the lower resonances upwards. This website states that the bell of a brass instrument both allows the instrument to project more, as well as increase the frequency of low notes, with the lowest fundamental pitches being raised up the most. The bell also gives the instrument a pedal note. A website created by the the University of New South Wales confirms that the bell of a brass instrument raises the fundamental frequencies of the horn and pitches up the upper harmonics of the instrument. In their two sound samples, the sample with a strictly cylindrical pipe sounds lower in frequency and more dull at higher frequencies than the sample of the pipe with a flare and bell. This happens because the longer waves in a conical horn will not ride the curvature of the horn as well as shorter waves, thus sounding higher in pitch due to experiencing a “shorter” horn. The shorter waves, in turn, ride the curvature of the horn well, experiencing a “longer” horn and radiating the notes better.

Scholars also confirms the presence of this phenomenon. Berkopec, of the Department of Physics in the University of Ljubljana, writes that the horn serves to amplify and raise the pitch of lower frequencies by shortening the perceived air column length for lower modes. Moore, from the Department of Physics at Rollins College, also affirms Berkopec. Moore says the longer wavelengths that go through the horn reflect earlier down the piping than shorter wavelengths, thus increasing the frequency of the lower notes. At the higher frequencies, this phenomenon is limited and the higher frequencies remain at their normal pitch. The bell raises the pitches up enough that the odd frequencies of the instrument line up with the even ones, providing the player with a full harmonic series. There appears to be unanimous agreement that the bell shifts the pitches of the lowest frequencies upward, although all the authors express the reason this phenomenon occurs, in different fundamental ways.

Hyperphysics and University of New South Wales also discuss the bell’s efficiency in radiating sound outwards, particularly at the higher harmonics of the instrument. This results in the characteristic “brassy” tone of brass instruments. Logie, of the University of Edinburgh, expands more about this characteristic brassy sound, which is essentially an increase in the power of upper dynamics and increasing number of upper harmonics present in the note and only present when the instrument is played at loud dynamics. Logie defines a brassiness potential, B, that is proportional to the amount of cylindrical tubing an instrument has. Instruments such as trumpets and trombones have higher values of B in comparison to gradually expanding instruments such as euphoniums and tubas, and thus sound more “brassy” and “bright”.

The acoustic phenomena of shock waves emanating from trombones that Hirschberg et al. write about is highly linked to the instrument’s “brightness”. Their experiment confirms that shockwaves can be formed from a trombone when it is played at fortissimo levels. Hirschberg et al. attribute this to instruments that start off cylindrical then quickly expand out into a horn, as their internal pressure can be kept high and permit for shock waves. On the contrary, more conical instruments are less capable, if at all, of producing shock waves because their conical shape allows the pressure wavefront to decay faster and consequently reduces the sudden pressure differences by having a larger cross sectional area in some part of the instrument.

The effects of more specific types of horns can be somewhat predicted using Horn Theory and Webster's Horn Equation, which was proposed by Webster in 1919 (Kolbrek). However, according to Kolbrek, Webster's horn equation is merely an approximation with many assumptions, and much of horn theory is unknown as it is complex and has not been thoroughly researched yet. Berkopec also mentions Webster's Horn Equation and states that it does give a sufficient approximation, indirectly confirming Kolbrek's statements.

Piping and Length

Pipe length is defined as the amount of tubing in the main body of the instrument, excluding the tubing on the valves. The pipe length to determine specific types of tubas depends on the bell effect according to a forum post from Tubenet, a forum dedicated to discussion about tubas. By the nature of physics, a BBb tuba is lower pitched than the Eb tuba, so it will require more tubing. Users DonShirer and Chuck(G) both mention the effect of the bell on the frequency of the notes, although they are not able to quantify how much this effect will change the frequency of notes. Chuck(G) provided a sample for how long a pipe must be to play specific notes for tuba, which may prove useful in the future:

F2 = 393.2 cm | E2 = 416.6 cm | Eb2 = 441.4 cm | D2 = 467.6 cm | Db2 = 495.4 cm

C2 = 524.9 cm | B1 = 556.1 cm | Bb1 = 589.2 cm | A1 = 624.2 cm | Ab1 = 661.3 cm

G1 = 700.6 cm | Gb1 = 742.3 cm | F1 = 786.4 cm | E1 = 833.2 cm | Eb1 = 882.8 cm

D1 = 935.2 cm | Db1 = 990.9 cm | C1 = 1049.8 cm

The cross section of the brass instrument piping increases as it nears the bell's end. Hirschberg et al. touches upon how the differences in the percentage of cross section that is cylindrical can determine how "brassy" the instrument sounds. Reiterating upon what was discussed in the bell section, the higher percentage of the cross section that is cylindrical, the more "brassy" an instrument can be.

In determining the particular sound of an instrument, the concept of impedance is discussed frequently. According to Berkopec, acoustic impedance is defined by the acoustic pressure over the volume flow. The difference between input impedance and output impedance is the acoustic impedance. At the end of the trumpet the pressure is close to atmospheric pressure because an antinode is there, thus yielding near zero impedance. Closer to the mouthpiece, the impedance is higher because the area is smaller and a huge pressure is applied by the lips. Berkopec also mentions end correction, which for a one closed one open ended pipe in real world situations is close to 0.61r, where r is the radius of the pipe. This is occurs because the length is equal to the acoustic length in a vacuum, and the acoustic length becomes larger than the actual instrument length due to sound radiation into the air.

Valves

The valves on a brass instrument control the total length of tubing that the buzzing travels through, affecting the harmonic series depending on how many valves are depressed. Most brass instruments have three valves, although some feature four or more depending, particularly euphoniums and tubas. Fundamentally, valves reroute the path the sound takes to the bell another path that is slightly longer.

The most common type of valves are piston valves, which move upwards and downwards, and rotary valves, which rotate when their key is pressed. A website from the National Music Museum talks about Allen valves, which are a variation of rotary valves that are longer and more slender than normal valves. This type of valve was created by Joseph Lathrop Allen in 1853 to create valves that are quicker action than conventional rotary valves. Their size reduces the space taken up by valves and decreases the friction required to activate the valves. In the center, the valve piping is significantly smaller and slimmer than rotary valves.

Depending on the valve depressed, a certain amount of tubing will be added to the instrument to drop the harmonic series down a half-step or more. Werden discusses the science behind these valve systems, focusing on playing a note exactly in tune. The three valves on a brass instrument are made to extend the tubing of the brass instrument by an amount that would tune the harmonic series specifically for those notes. For example, when the second valve is pressed, an additional 6% of tubing will be appended to the instrument, converting a 100” long tube to about 106”. A problem arises when using multiple valves to lower the instrument, such as the valve combination 1 and 3. Pressing this combination would give 124.86" of tubing, but 125.99" of tubing is necessary to be in tune. To combat this issue, compensating valve systems were invented to make the instrument more in tune by adding additional tubing to make the instrument longer when those valve combinations are pressed. These type of valves systems can be found on euphoniums and tubas, of which commonly require the use of multiple valves at once.

Mouthpiece

The mouthpiece of the instrument is where the player buzzes into to produce the sound of the brass instrument. It slots into the leadpipe and can be exchanged depending on the player's preference. The part of the mouthpiece that the player puts their mouth on is the rim, and the rim connects to the cup. Inside the cup, the air stream of the player gets funneled to the bottom of the cup, where it passes by the throat of the mouthpiece and into the backbore. After leaving the backbore, the air stream leaves the mouthpiece and enters the leadpipe to travel through the instrument.

Hyperphysics, while supplying information about bell, also gives insight to the effect of the mouthpiece. The mouthpiece forces the upper resonances of the instrument downwards and emulates a cavity resonator. Cavity resonance happens when an air cavity has air that is pushed into it and the pressure on the inside of the cavity pushes the air back out, effectively causing a spring-like effect and resonating at a single frequency. The effects of a cavity resonator are caused by differences in pressure within the cavity when the air is moved in an oscillatory motion. The resonant frequency of the mouthpiece cavity resonator is high and as the frequency the player buzzes approaches the resonant frequency of the mouthpiece, the perceived length of the instrument increases, and the pitch of the higher notes is lowered. University of New South Wales confirms this effect of the mouthpiece, repeating that the mouthpiece serves to lower the highest resonances and empower some other resonances. Moore also provides information on the mouthpiece in that a trumpet mouthpiece primarily increases the impedance between 200 Hz and 1500 Hz, which is the primary range for a trumpet. Shallower cup depth mouthpieces can help with extreme high ranges by increasing the resonance frequency of the mouthpiece to allow for easier playing. Hyperphysics and UNSW diverge from Moore somewhat on this last point, but all agree that the mouthpiece does effect the sound of the instrument.

Yamaha has a few articles discussing the more intricate modifications to the mouthpiece that may can affect the sound of the instrument. One article discusses the cup and rim modifications. For the cup, the cup diameter, depth, and shape can be customized. For the rim, the rim contour and bite can be customized. The cup width is the distance between sides of the cup of the mouthpiece. A smaller rim will typically increase the player's ability to play high notes and increase the stamina of the player, but will restrict the player's ability to use a larger volume of air. A larger diameter will do the opposite: increase flexibility, make low notes sound more full, and give a larger volume of sound at the expense of stamina. The cup depth describes the depth of the cup of the mouthpiece. Shallower cup depths have the same effect as smaller cup diameters, but will also change the sound of the instrument to be brighter. Deeper cups will produce a darker tone and make low notes pop, but higher notes will be more difficult to play because there is so much more space in the mouthpiece that higher notes will be much more difficult to support. The inside cup shape of the mouthpiece changes the path of the air and how it will move. "U"-shaped cups will yield a brighter sound and more support in the higher registers and conversely, "V" shaped cups make the horn sound darker and allow low notes to project. The rim contour and thickness affect the feeling of the mouthpiece to the player and affect the sound that way. Thicker or wider rims will give the player better lip contact onto the mouthpiece, increasing endurance and making high notes easier. Thin or narrow rims give the player more control and flexibility, but are more fatiguing and sometimes uncomfortable. Rim bite, although seeming similar to rim contour, is different because it addresses the steepness and sharpness of the transition from the rim to the wall of the cup. Sharper bites typically make the sound more refined and precise, but too sharp of a bite may be painful and make transitions between notes difficult. Rounded, soft bites will generally be more comfortable, but sacrifice precision and blur notes sometimes.

Another Yamaha article talks about the throat and backbore of the mouthpiece. The throat is the transition of the mouthpiece from the cup of the mouthpiece into the rest of the mouthpiece and instrument and is the hole at the bottom of the cup of the mouthpiece. The narrower and longer the throat, the less air is required and the faster a response comes, also making the instrument sound more brilliant and making high notes project more. A larger bore, on the other hand, opens up low notes and permits a larger volume of air to be used. However, when more air is used, the player can fatigue more easily. The backbore begins from the end of the throat and expands to the end of the mouthpiece that is put into the instrument. Narrower backbores expand more gradually than wider backbores and the larger and wider the backbore, the more the lower notes benefit, similar to most of the other characteristics of the mouthpieces.

Finally, Yamaha discusses the weights and finishes of mouthpieces. These factors have a significantly smaller effect on the sound of the instrument, but nevertheless change the sound. Harder materials, such as nickel silver, stainless steel, and solid Sterling silver, typically do not absorb as much of the buzzing as softer materials, thus increasing the amount of energy put into the instrument and its power. In mouthpieces made of softer materials such as woods and plastics, more energy is absorbed, so the sound loses much of the cutting and power and the instrument sounds warmer. However, these mouthpieces can be very preferable in extreme weather situations where they would be far more comfortable to use than hard metal mouthpieces. The weight of the mouthpiece also affects the sound of the instrument, with heavier mouthpieces sounding more powerful because its heft makes the mouthpiece more stable during playing. Heavier weighted mouthpieces are useful when it is necessary to project over many musicians in, for example, an orchestra. Lastly is the finish of the mouthpiece, which changes the feel of the mouthpiece drastically. Silver is the most common due to its affordability and reliability. Gold is also used, but it is costly and makes the mouthpiece feel softer and more comfortable for some people, especially to those with silver allergies. Overall, much of the Yamaha articles seem especially nitpicky and not entirely believable, although they are a well-established company that manufactures quality instruments.

3D Printing

Notable Projects for Low Cost 3D Printing

Similar to many other machining processes, 3D printing began as an expensive process and has become cheaper as more research has been done in its field. Notable projects created by researchers and prosumers have sparked much interest and innovation in additive manufacturing. One such example is the RepRap project, an open source 3D printer that is intended to self-replicate itself. RepRap, standing for replicating rapid prototyper, was the first machine in low-cost 3D printing that brought additive manufacturing to the consumer market. In 2017, RepRap was voted the most significant 3D printed object, and its creator, Adrian Bowyer, received the Outstanding Contribution to 3D Printing Award. One researcher took a survey about what 3D printer people use, and it was discovered that over 25% of people use a RepRap project printer, the highest percentage of all the different types of 3D printers.

Jones et al. discusses the RepRap project up to 2011. They begin by defining RepRap as a "kinematic assisted self-replicating and self-manufacturing machine", which is a moving machine that can only replicate itself with assistance and can create some or all of its parts. As such, cost would be minimized. The origin of RepRap was the concept that RepRap machines could create useful products for people when not reproducing itself, similar to a mutualistic or symbiotic relationship. They document their process and design choices they made to create such a machine, beginning with their RepRap version one, "Darwin", and then their second version, "Mendel". The RepRap project was highly successful, with over 4500 machines in 2011, and was a forerunner for low cost additive manufacturing. Due to the nature of Darwinian selection, a poorly made RepRap would have to become better in order to survive, and thus the project would almost be self-sustaining and with RepRaps evolving as time goes on. They also say that they are no longer in control of the project and will let the people and community control it, dedicating all developmental success to those people.

Further expanding on the low-cost 3D printing market, The Creative Machines Lab at Cornell University discusses their FAB@HOME Model 3 and explains their motives for creating such a machine. This machine was made in 2011, before 3D printers became as casual as modern time. Back then, machines were expensive and relatively new, so it was difficult to obtain a 3D printer in the first place. The FAB@HOME is a device that is highly customizable in the processes that it can do, only requires simple tools to assemble, and most importantly, costs under $1000. FAB@HOME began with the concept of open source hardware and is their priority when designing iterations. Between the Model 2 and Model 3, the team realized the need to simplify the building of the hardware, so they removed the thermoplastic inserts that required using a soldering iron because they deemed it to be intimidating for non-technical users. Also, the variety of tools that the FAB@HOME Model 3 can use now include vinyl cutting, pen plotting, plastic printing, and more, permitting more flexibility for the user to create things. The FAB@HOME Model 3 is an extremely versatile machine that, now with its simplicity, can allow educators and children to have a machine to use. Both FAB@HOME and RepRap demonstrate solutions to a growing market for low-cost additive manufacturing.

Usage

Due to the countless possibilities of additive manufacturing, many outstanding people have created concepts and works using 3D printing. 3D Systems depicts Norwich University's use of 3D printed parts in their autonomous underwater vehicle. Blake Shaffer, one of the university's team members, was astounded that a finished part could be created simply by dipping a printed part into a hardener. Their school has a ProJet CJP 360 3D printer and they opted to use it to construct parts instead of using their school's machine shop. The main benefit to the team of using 3D printed part is that they would not have been able to create as complex of parts as they did in their machine shop. The team says that using 3D printing probably saved them over "$5000 and several months of manufacturing time", a drastically large figure.

While 3D printing end-use parts is amazing, it is less unconventional than some other 3D printing endeavors. Danit Peleg is a fashion designer who completely 3D printed a five piece fashion set from her home for her graduate project. She designed a 3D printed dress for Amy Purdy to showcase at the 2016 Paralympic Games and 3D printed her skirt for her TED Talk the night before. Peleg focuses on her story of using experimenting and tinkering with fabrics and materials for fashion design, eventually leading her to 3D printing. She began trying to 3D print clothes for her senior collection at fashion school, but was unsuccessful at first due to her lack of knowledge about 3D printing. Later, she interned at the New York fashion house by helping design and create stunning dresses using 3D printing, although these dresses were too rigid and occasionally scratched the models. Bent on finding a better alternative, she travelled to her local makerspace to learn as much as possible about 3D printing, to the point that the owners let her stay overnight to tinker with the printers. Here, she discovered flexible filament that is a better fit for clothing. She concluded with the idea that some day, one could easily 3D print clothing that match their exact dimensions according to their own liking.

Printing clothing may seem absurd, but there are more wild uses of additive manufacturing, such as medicine. Dan Kraft begins by talking about the struggles of prescription drugs, specifically how the top ten grossing drugs only work for about 1/4 to 1/23 people who use them. And with that, those drugs can have negative side effects. Kraft says that we are still stuck in a time where drugs are imprecise and estimated, and that we can make medicine more precise, saving money and lives. One solution he proposes is the polypill, a pill that contains many different medications in differing amounts so that they can work synergistically with one another. However, polypills are usually premade and not adapted for the specific individual. But, developing upon this concept of a polypill, he developed IntelliMeds, which are 3D printed polypills that would contain specific dosages for each individual, printed daily. IntelliMeds would start with an empty capsule, then be filled with various quantities of micromeds, which are extremely small doses of common medicine, and finally have other data imprinted onto each pill for each patient for easier tracking. These three articles show the wide scope that additive manufacturing is being used in, and how some appear to be absurd ideas but work.

Effect on Business

Additive manufacturing began in the industrial sector, but for an overwhelming majority of companies it was obscure. Now, as additive manufacturing is becoming more mainstream, more companies are considering using additive manufacturing in their business, whether for prototyping or end-use products. Olivier Scalabre, an industrial systems thinker and Head of the Boston Consulting Group's South America, West Europe and North Africa operations, predicts what the world's next manufacturing revolution will be. He states that the world is currently arriving at a point of little growth, which is a significant problem for economies. Scalabre's thesis is to combine the divergence between manufacturing and technological innovations to increase productivity, and that this idea defines the next technological revolution that has already begun. Scalabre says that additive manufacturing has proven to benefit the plastics industry and is making progress in metals, both of which combined make up 25% of global manufacturing production. He provides an example of aerospace industries using 3D printing to merge 20 parts of a fuel nozzle into one single part, which led them to 40% more productivity and 40% more growth. Returning to his main point, Scalabre characterizes this new revolution as the ability to create custom, precise parts with the speed and cost of rigid factory manufacturing. This idea will drive supply chains back into their home economies, make them more flexible, efficient, better environmentally, and most importantly, increase productivity locally. Trade markets will be focused on region instead of producing products internationally and then shipping them to their target market.

Providing opposition to Scalabre, Petrick et al. talks about how 3D printing poses a threat and can disrupt manufacturing. They note that 3D Systems 3D printed a hammer at the

November 2012 EuroMold fair and The Economist wrote how expensive asking a current factory to create one custom hammer would be, but producing a lot would be significantly cheaper due to economies of scale. Petrick et al. recalls that The Economist explains how economies of scale matter far less with 3D printing, allowing the model to be tweaked to one's liking. 3D printing will force many companies to reconsider their current strategies because 3D printing has the ability to make highly customizable economies-of-one economically viable. Furthermore, Campbell et al. created Strategic Foresight Report based on the effects of 3D printing and additive manufacturing on the world. This report, published by the think tank Atlantic Council, introduces two unique ideas of the effects on additive manufacturing, among other ideas posed in the article, being that its presence can add to the forefront of research development in disciplines such as NBIC (nanotechnology, biotechnology, information technology, and cognitive sciences) and that it can pose a disruption to traditional manufacturing and the economy. Both Petrick et al. and Campbell et al. view additive manufacturing as a disruption to industry, although they both mention its benefits, so they appear to be taking a more negative stance against additive manufacturing compared to Scalabre.

Deutscher et al. begin with their answer to the question of what the reality is of 3D printing in industry and consumers, stating that it will be a huge game changer in industry, and it will be effective far closer in the future than many people expect. As a result, companies should look into 3D printing options now before adoption too late will set them far behind their competitors. 3D printing is valuable because it is the first industrial means of production to be flexible, be economically viable for creating single objects, and be able to customize products, whether complex or not. As this new tech progresses forward, the industry will be changed, with some companies benefitting and others losing. Especially to smaller companies and entrepreneurs, 3D printing allows them to prototype and create ideas quickly and cheaply than any other means, lowering the entrance barrier, according to Eduard Neufeld. However, companies that make industrial goods will be disrupted by consumers creating their own versions of goods at home, whether legal or not, and “transportation and logistics providers”, such as shipping companies, might also be hurt because people can instead 3D print things at home and locally instead. Deustcher et al. distinguish that 3D printing certainly will not replace traditional manufacturing methods such as molding and casting, but will merely augment them and allow for more options of manufacture depending on economics, such as printing one specific and more complex component and casting another. Speaking more specifically on when 3D printing will affect the market, BCG predicted about 2017 based on the launch, acceleration, and mainstream timelines of other innovative products. Companies in 2013 still have time to react to these changes, but the economy is nearing the “inflection point”, where it will become mainstream and companies that are negatively affected will face the tolls. Also, more research is being done in other aspects of 3D printing, such as 3D scanning, variety of materials, and increasing strength, which may decrease the time that companies have to react before some innovation jettisons 3D printing forward. They conclude that 3D printing will change industry, necessitating companies to change their strategies and logistics, as well as up the work that their IT must do to maintain and install the infrastructure needed to run these systems. Compared to the otehr three, Deustcher et al. takes a more middle and seemingly unbiased view of 3D printing, considering both its benefits and drawbacks.

3D Printed Instruments

Various 3D printed instruments have been created by scholars to test their viability. Most notably, Zoran and his 3D printed flute. In his preface, Zoran notes that the instrument making community highly standardizes the construction of musical instrument, so much so that deviating from commonplace is frowned upon. He decided that researching the possibility of a 3D printed concert flute would open up many avenues and allow the discussion of 3D printing and other fabrication technologies for use in assembling musical instruments. Elaborating on the standardization of musical instruments, Zoran explains that instruments evolved to become increasingly complex to permit for more expressiveness in the most skilled of players, leading to standardization of those instruments due to their potential. However, standardization of such complex instruments, while making them more popular, also increases the complexity of mass producing them, for a less common instrument and not mass produced instrument is far easier to innovate on and standardize than a more common but more complex instrument. In contrast to his background, Zoran decides to test the viability of a 3D printed flute. He starts first by using FDM printing to print an ABS flute, which took four days to print in nine different parts. The pads were originally printed with the keys of the flute, but air would escape, so felt pads were later glued on. Also, printed ABS springs did not work, so they were replaced with metal springs. One successful thing was the flute's lip plate, which Zoran remarks worked played easily. His next flute revision was printed using the Object Connex500, which can create prints of a higher resolution than the other FDM printer. This flute was far more successful than the other flute, notably being able to play more notes than the first flute. This flute took only 15 hours to print, was more watertight than the other flute, and had certain parts printed in more adequate materials. However, due to the plastic requiring to be UV cured, the flute warped only after 3 weeks. While the resolution and quality of 3D printing is not up to par, Zoran is faithful that 3D printing will provide a means for creating new, innovative instrument designs.

Focusing on brass instruments, Gibson et al. discusses the considerations for creating an intermediate level trumpet using 3D printing, one that is better than conventional plastic instruments such as the Tromba. They first discuss common materials to be used in 3D printing, such as ABS, Polyamide, and PLA. PLA is not suitable because it usually is brittle. ABS and PLA would both struggle because their printing process, FDM (Fused Deposition Modelling), is liable to cracking between layer, thus producing an incompatible instrument. Polyamide is the best out of the three, as it is strong, flexible, and durable, as well as being able to be combined with powdered aluminum to form Alumide, which would provide a more accurate sound quality to that of brass instruments. They also mention how another process, CLIP (Continuous Liquid Interface Production) can create smooth walls. Next, they begin to discuss design considerations, such as the timbre, the bell, and the leadpipe. The largest effect on the timbre, although inconclusive, seems to be the bell of the trumpet. If the vibrations of the wall of the trumpet can be dampened, then the power of the fundamental can be increased by almost 3 dB. Pertaining to the valves, in plastic instruments such as the pTrumpet, fast playing is severely hindered due to the friction as the plastic valves and valve blocks move against each other. Thus, Gibson et al. discuss hybrid valves, with a 3D printed inside and metal sleeve. The authors, using their research, fabricated a hybrid trumpet, consisting of both metal and plastic. They printed the instruments in China using SLA technology on UnionTech Lite450 SLA 3D printer, then electroplated the instrument with gold lacquer. They also conducted toxicity testing to test whether the instrument was suitable for playing. The results of their experiment showed that the sound of the instrument to observers had less “edge” and a “more rounded” sound. They conclude that it is possible to create intermediate level trumpets using composite materials, with their intonation and timbre being similar. The results between Zoran and Gibson et al. are different, although Gibson et al. managed to create a functional trumpet that performs well. However, other than images of the trumpet, they did not provide sound samples, so the audience does not know what the trumpet sounds like.

Contrary to other sources, Brackett et al. were not able to create a functional 3D printed instrument at all in 2008. Brackett et al. discusses how viable end-use rapid manufacturing brass instruments are with respect to optimizing resonance through making parts stiffer. For their experiment, they created two instruments, a pocket trumpet, chosen for its high complexity, and soprano trombone. These were reversed engineered by scanning the two in a coordinate measuring machine, then printing them at 0.1mm layer heights using Somos Watershed 11200 resin on a SLA7000 machine. The main limiting factor during testing was the limited tolerances when printing the instruments. Particularly with the pocket trumpet, air leaking was a huge problem. In conclusion, at their time of testing, rapid manufacturing is not very plausible for constructing instruments, but they are hopeful that things could change in the future with better manufacturing techniques. All sources are confident that in the future, additively manufacturing instrument parts can become a reality, but Zoran and Brackett et al. were not able to construct functioning instruments as Gibson et al. supposedly did.

Conclusion

This literature review provides the research necessary to understand brass instruments and figure out if a plastic brass instrument is viable at the moment. Currently, there is no definitive black or white solution, although, that being said, plastic brass instruments have been created in the past. This review of literature concludes that it can be possible to use additive manufacturing in the construction of brass instruments, although there are certain aspects and parts of the brass instrument design that have to be manufactured using separate means in order to be successful. An instrument created entirely using additive manufacturing is about as feasible as an artist doing wire management: surely it will look beautifully done, but it will not be guaranteed to work at all.

The research compiled about the physics of brass instruments is plentiful and likely sufficient to give most people enough understanding to begin designing their own brass instruments. It also provides enough information for future researchers to gain background on the fundamentals of brass instruments and delve into conducting their own research. Documents of 3D printed instruments fundamentally demonstrate that the concept of additively manufactured instruments are feasible, particularly with the success of the intermediate level trumpet. However, there are many limitations to this research. The Brass Instrument section, with exception to the Bell and Material, has not been confirmed with studies and is thus encyclopedia information that has not been evidently verified. The mouthpiece section in particular is suspect to bias and dominated by information from Yamaha that has not been backed up by thorough research and studies. The 3D Printing section of the paper could also use some work, particularly in the Notable Projects, with background history. Furthermore, this literature review raises many questions on other possible research. Are there questions about whether some sources believe additive manufacturing to not be revolutionary? Are there any completely failed 3D printed instruments where the researchers only had negative things to say?

The next steps in research would be to find counterarguments to the current sources and compare their trustability compared to the current compiled sources. Also, if such a plastic instrument were to be created, the tools and other means required to construct the instrument must be researched.

Part 3 - Primary Research

PVC Tuba Body

Introduction

In this research segment, the topic of material on the sound of the instrument body is investigated. Specifically, whether it is feasible to construct a brass instrument out of non-metallic materials such as plastics. In secondary research, the success of non-metallic brass instruments has shown to be plausible, performing surprisingly well. For example, Cool Winds instruments are made entirely of ABS plastic, and according to some sources, function just as well as their counterparts, albeit having more flaws in sound and playability. A few researchers have delved into the concept of strictly using 3D printing to construct brass instruments, although their findings have been mixed. Most of those researchers that have not found tremendous success with their research are hopeful for the future of additive manufacturing for augmenting musical instruments.

From the research and materials accessible, it was determined that the first step into primary research was to construct a body of the tuba using PVC pipes due to their relatively low cost and ease to work with.

The body of the plastic tuba thus far

Design Considerations

A major design consideration for this revision of the tuba body was that the pipe diameters expand as the cross-section of the tuba nears the bell. During the research, this concept was stressed primarily for its projection, but also for the distinct warm sound of the tuba. This was not able to be replicated exactly in the same manner as a tuba, however, the current shape is acceptable.

Another minor consideration was that the tuba should be designed for marching. For an upright tuba, most of the sound is projected upwards and becomes more muted. The benefit of a marching style instrument is that the sound projects forward and it looks far more interesting than a conventional tuba due to its position while playing on the shoulder of the musician.

Tone Quality

There is a bit of warmth to its sound, but obviously lacking when compared to a more professional instrument. Its tone quality is rather full and does not indicate leakiness anywhere in the instrument, despite each of its PVC parts held in place without permanent adhesives like PVC glue. This may be due to PVC pipes being rated to withstand certain pressures of fluids, and due to this, the manufacturers may have done tests to ensure that all linkages maintain pressure in the system and do not leak.

3D Printed Valves

Introduction

This section discusses the next assembly within the plastic tuba--- the 3D printed valves. The valves on a brass instrument change the harmonic series of the instrument by elongating the instrument. When the valve is depressed, the perceived length of the instrument is increased and thus the harmonics change. By combining various harmonics, the brass instrument can play chromatically.

Plastic valves have been created before by instrument manufacturers such as Cool Winds. In Cool Winds instruments, the valves casings are created using injection molded plastic, although they do feature a hybrid valve, which uses metal sleeves on the inside of the valve to further decrease friction.

In order to test the feasibility of 3D printed valves, an experiment was devised to test various valve designs in an attempt to determine which print settings work the best for creating a valve that combines the best aspects of airtightness and ease of use.

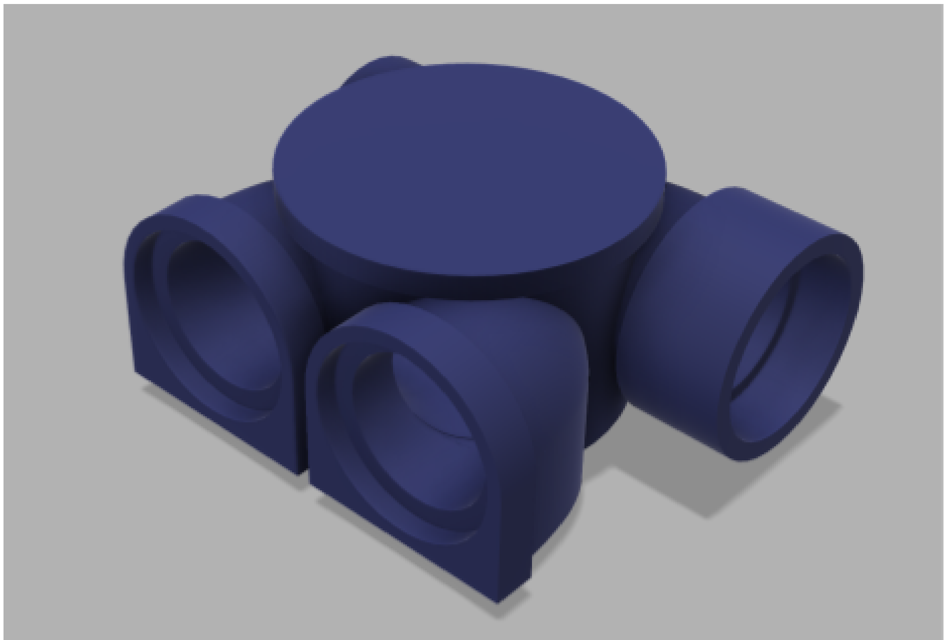
Iterative Design Methods

A. Objective
    1. To determine the design and print settings that allow for the most optimal 3D printed valve to be created, based on leakiness and lack of friction.
B. Materials
    1. Printers
        i. 2014 FlashForge Creator Pro
        ii. Flashforge Finder
        iii. Kodama Trinus
    2. Filament
        i. Flashforge PLA
        ii. Bumart PETG
    3. Materials for Testing
        i. Anemometer
        ii. Electric Fan
C. Procedure
    1. Designing
        i. Create a first prototype of the valve
    2. Printing
        i. Determine print settings for valve depending on what needs to be tested

        ii. Send the file to print on one of the printers available
3. Testing
    i. Leakiness Test
        1. Objective - determine if the valve leaks air and where those leaks might be
        2. Procedure
            a. Test air velocity of the electric fan
            b. Connect the valve to the anemometer and electric fan
            c. Read the anemometer for air velocity
            d. Compare results with initial velocity reading
    ii. Implementation in Tuba Body
        1. Objective - determine qualitatively whether the valve will still permit sound to be created
        2. Procedure
            a. Attach valve to tuba body
            b. Buzz into the mouthpiece and note the sound
4. Revising
    i. Based on testing, determine what the shortcomings of this design are
    ii. Ideate what should be done to remedy the issues
5. Repeat the procedure and modify the valve design

<u>Prototypes</u>

- Valve v1
    - Valve v1 was the first design of a 3D printed valve. This design had the turn stem for the valve on the opposite side of the cover. Also, the connectors on each side of the valve casing had diameters of 25mm. One of the design characteristics was to make the valve easily printable by reducing unnecessary overhangs.



A render of the valve

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- Valve v2
    - A modification of valve v1. This version increases the diameter of the connectors on each side of the valve casing to 26.67mm, or the diameter of a ¾” PVC pipe, to allow more convenience and fewer adapters. Also, in this revision, the turn stem is positioned on the same side as the cap in such a way that the turn stem protrudes from the cap.

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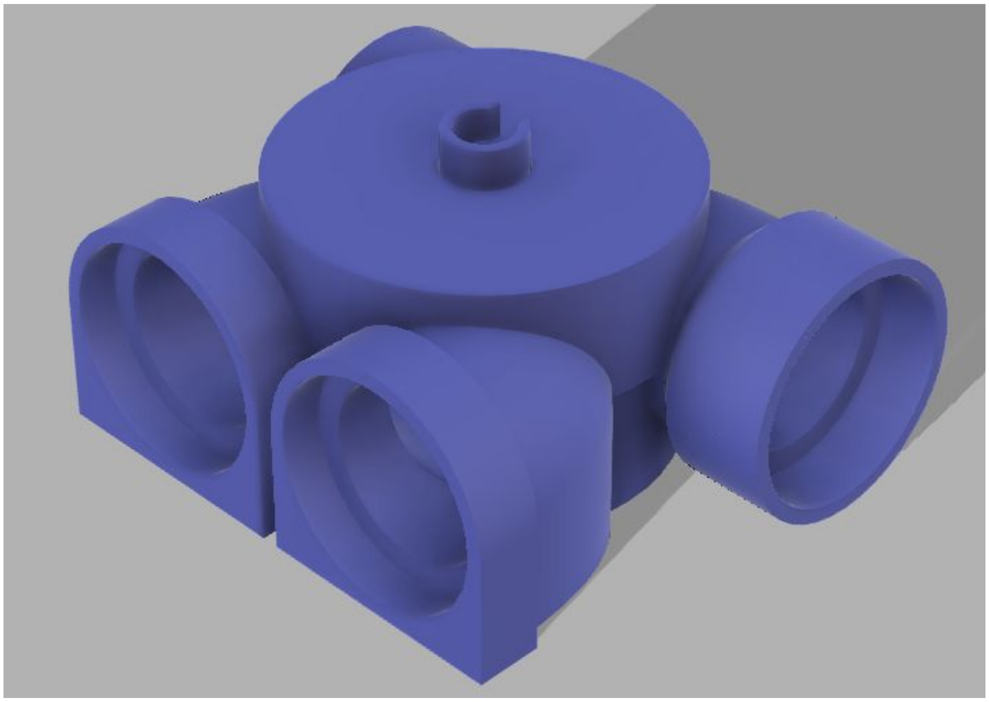
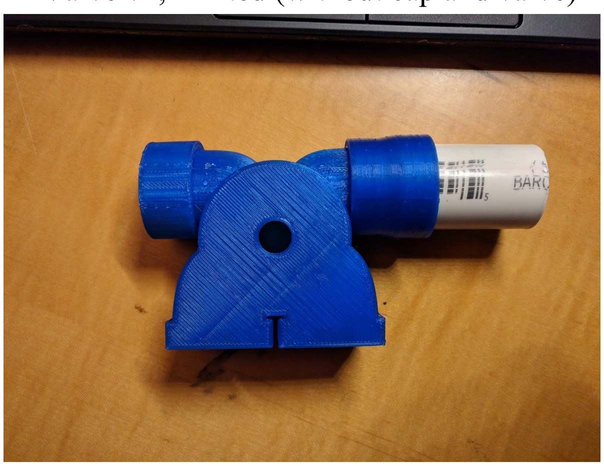
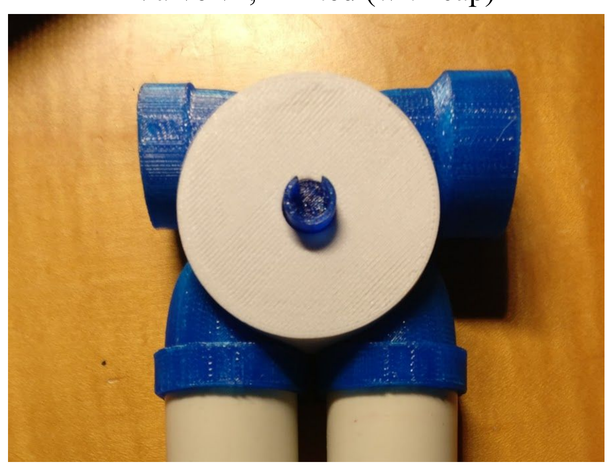


- A render of the valve

Valve v1, Printed (without cap and valve)



Valve v2, Printed (with cap)



Experiment

Introduction

The formal experiments performed were eight matched-pair T-test comparing the control to various permutations of valves. For example, two separate tests were conducted on whether valve v1 in place would have an effect and whether valve v1 in place and its cap attached would have an effect. The fan speed, length of tubing, and position of anemometer were all controlled. The independent variables were whether the valve was in place, whether the cap was in place, and whether the valve was depressed. The dependent variable was the measured air velocity by the anemometer. In order for the test to be statistically valid, the following conditions must be addressed:

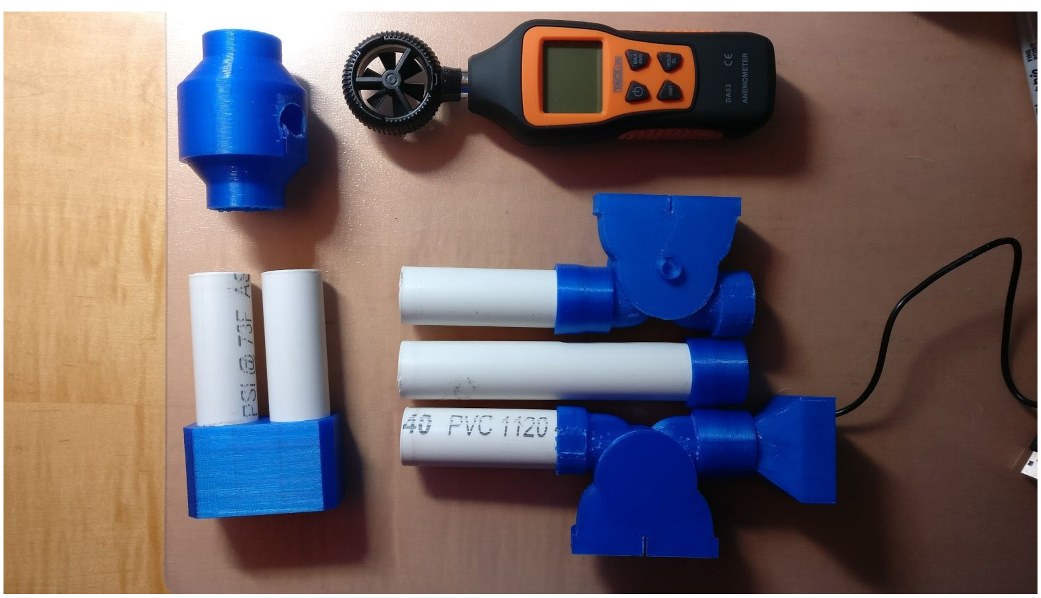
Assumptions / Conditions

- *Paired Data:*
    - The data is paired because the tests are adding on to the control and are not independent of it.
- *Randomization:*
    - The trials could not be randomized; the experiment will proceed with caution.
- *10% Condition:*
    - The trials are less than 10% of all trials that can be conducted for air velocity (the amount is theoretically infinite)
- *Nearly Normal:*
    - The distribution of the differences is not nearly normal because much of the data points should be the same for each trial for consistency. The experiment will proceed with caution.

Materials

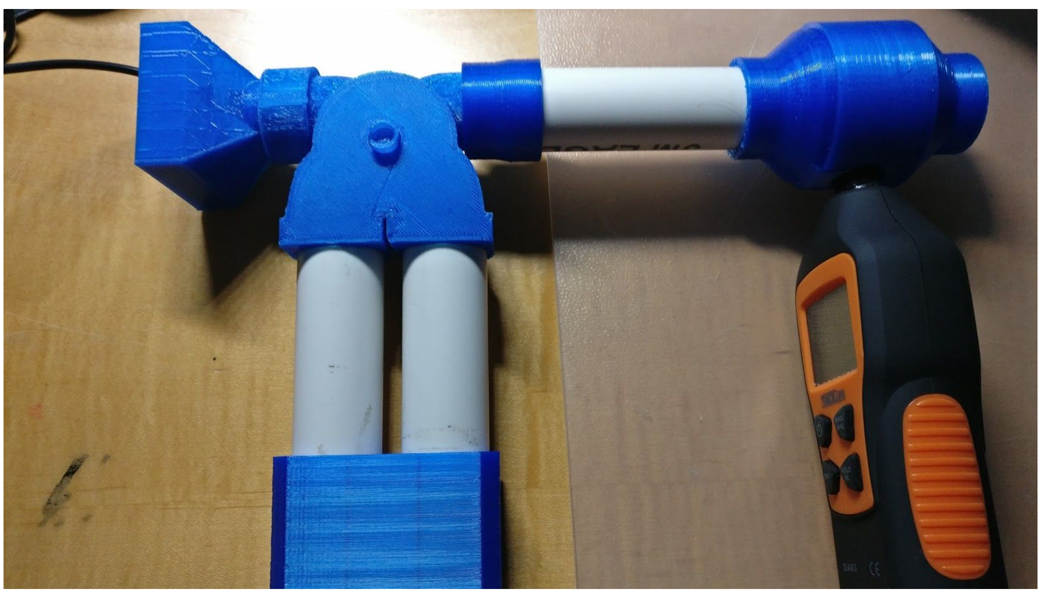
- TACKLIFE Handheld Anemometer
    - https://www.amazon.com/dp/B07FW12LVX/ref=cm_sw_em_r_mt_dp_U_D90ZCbE0EN9GV
- 40mm x 40mm 5V 0.2A USB fan
    - https://www.amazon.com/dp/B074YJH3P9/ref=cm_sw_em_r_mt_dp_U_g.0ZCbGNHW44D
- One 5.5” ¾” Schedule 40 PVC pipe
- Four 3” ¾” Schedule 40 PVC pipe
- Three 25mm to ¾” PVC pipe adapters
- One fan to 25mm adapter
- One anemometer enclosure
- One extra piping connector
- Valve Assembly v1
    - Casing v1
    - Valve v1
    - Cap v1
- Valve Assembly v2
    - Casing v2
    - Valve v2
    - Cap v2
- USB power source

Apparatus



All of the apparatus components

- *Top Left*: The PVC to anemometer to PVC adapter. This component encases the fan of the anemometer and allows the air to travel from the PVC through the anemometer in a closed system.
- *Top Right*: the anemometer. Measures the air velocity that goes through its fan
- *Bottom Left*: the extra PVC piping the air travels through when the valve is depressed. In a functional tuba, this component is the extra piping that is added to the length of the instrument, lowering the harmonic series of the instrument.
- *Bottom Right*: the independent variables and fan (attached to the lowest of the three). All of these must be the same length to ensure an unbiased test. The top is valve v1, the middle is the control, and the bottom is valve v2 with the fan attached.



The apparatus assembled for the “Valve v1” test

The apparatus ensures that air is displaced by the fan through a closed system, including the independent variable and some amount of ¾” PVC piping, and to the anemometer. The anemometer will measure the air velocity and display it on the LCD display.

Procedure

1. Gather the components for the experiment.
2. Assemble the components as seen in the component picture above.
3. Enclose the anemometer in the anemometer adapter.
4. Attach the control between the anemometer and fan assembly.
5. Turn on the anemometer.
6. Plug in the USB of the fan into a power source.
7. Let the anemometer stabilize at a consistent measured air velocity.
8. Record the air velocity for that trial.
9. Unplug the USB.
10. Let the anemometer read 0 m/s.
11. Repeat steps 6-10 nine more times.
12. Switch out the control with valve v1 and reassemble the apparatus with valve v1.
13. Repeat steps 6-10 ten times.
14. Add the cap onto valve v1.
15. Repeat steps 6-10 ten times.
16. Remove the cap and turn the valve so the airflow is redirected through the extra piping such that the valve is depressed.
17. Repeat steps 6-10 ten times.
18. Add the cap back onto valve v1.
19. Repeat steps 6-10 ten times.
20. Switch out the valve v1 with valve v2 and reassemble the apparatus.
21. Repeat steps 13-19 but with valve v2 and its components.
22. Clean up the experiment.

Part 4 - Findings

PVC Tuba Body

Reception of the Instrument

The sound of the tuba body is surprising to many and seems to spark curiosity. It was played in front of teachers in a casual presentation scenario, and many were surprised by its sound. One physics teacher, who also plays the flute, inquired about whether the instrument's material has an effect on its sound. Also, one of the overseers of the CAPStone program, Mr. Chinosi, was also surprised by the tuba body's sound. He remarked about how the instrument had a warmth to it that he did not expect, and that it sounded close to an actual tuba.

In addition, the tuba body was demonstrated in the portal connection with the Afghanistan National Institute of Music (ANIM). After performing a short excerpt on an actual tuba, which ANIM did not have, the plastic tuba was shown to the students there. They were intrigued that it made sound and inquired further as to how it works.

3D Printed Valves

Informal Tests and Observations

Initially, while experimenting with valve v1, the control air velocity without a valve was measured to be 1.1 m/s. Once the valve was attached, the air velocity dropped to an average of around 0.7 m/s. This led to some doubts as to the air leakiness, however, minimal amounts of air leakage were felt. A small amount was perceived from the gap between the valve and the casing, although that could be due to the suction of air by the electric fan outside of the apparatus. Attaching the cap to the valve casing increased the air velocity to 0.8m/s, so the minor air leakage may have been from the aforementioned gap.

When valve v1 was attached to the tuba body, the tone quality was unexpectedly sonorous. The tone cracked at higher pitches, specifically anything above middle Bb on the tuba. However, the contrabass Bb and bass F sounded as if the valve was not attached. All of these results were surprising given the decrease in air velocity from earlier, as it was expected that the valve would not permit a warm sound. Furthermore, when the valve was depressed, the harmonic series of the tuba body indeed shifted downwards. This revision sounded worse than the test prior, but the sound for the contrabass A and bass E still sounded as sonorous as the contrabass Bb and bass F.

The control air velocity the day of testing valve v2 was measured to be 1.5 m/s, which was greater than the control air velocity for valve v1 despite similar research conditions. Attaching the valve, the measured air velocity decreased to 1.0 m/s. Subtracting the initial air velocity from the air velocity through the valve, the change in valve v2 was more than the change in valve v1 by about 0.1 m/s. Around the valve, there was no perceived air leakage, not even from the gap between the valve and the casing. The fit of the valve between the casing in valve v1 was looser than valve v2, so if valve v2 was more airtight, this might suggest that the air velocity might not be linearly proportional through rough surfaces (the higher the air velocity, the more decrease in air through the same rough area). Once valve v2 was depressed, the air velocity dipped to an average of 0.4 m/s.

Although not pertaining to the tuba body, one interesting note during testing was that there was a decrease in measured velocity throughout the apparatus when the length of tubing was increased. This was experienced even without the valve attached, so this casts some doubt onto the consistency of the results because it demonstrates that the longer the pipe, the larger of a factor it is in decreasing the perceived air flow.

Another interesting note was that if either end of the airflow were to be covered, even slightly, the air velocity would drop significantly. Blocking the entry or exit point of the air seems to cause the rate at which air moves to decrease, thus decreasing the amount of velocity. This could possibly explain the decrease in measured velocity as the length of the tubing increases.

Experiment Results

<u>Data</u>

Terms

- *V1:* tests pertaining to valve v1.
- *V2:* tests pertaining to valve v2.
- *None:* tests without any other modifiers to the valve assembly; testing the effects of only the casing and the valve.
- *Cap:* tests with the cap attached to the valve.
- *Dep:* tests with the valve turned so that it is depressed and with the airflow redirected through the extra piping.

	Air Speed (m/s)								
Trials	Control	V1				V2			
		None	Cap	Dep	Cap Dep	None	Cap	Dep	Cap Dep
1	1.1 m/s	1. m/s	1. m/s	.5 m/s	.5 m/s	1. m/s	1. m/s	.4 m/s	.5 m/s
2	1.1 m/s	1. m/s	1. m/s	.5 m/s	.5 m/s	1. m/s	1. m/s	.4 m/s	.4 m/s
3	1.1 m/s	1. m/s	1. m/s	.5 m/s	.5 m/s	1. m/s	1. m/s	.4 m/s	.5 m/s
4	1.1 m/s	1. m/s	1. m/s	.5 m/s	.5 m/s	1. m/s	1. m/s	.5 m/s	.4 m/s
5	1.1 m/s	1. m/s	1. m/s	.5 m/s	.5 m/s	1. m/s	1. m/s	.4 m/s	.5 m/s
6	1.1 m/s	1. m/s	1. m/s	.5 m/s	.5 m/s	1. m/s	1. m/s	.5 m/s	.4 m/s
7	1.1 m/s	1. m/s	1. m/s	.5 m/s	.5 m/s	1. m/s	1. m/s	.5 m/s	.4 m/s
8	1.1 m/s	1. m/s	1. m/s	.5 m/s	.5 m/s	1. m/s	1. m/s	.4 m/s	.5 m/s
9	1.1 m/s	1. m/s	1. m/s	.5 m/s	.5 m/s	1. m/s	1. m/s	.5 m/s	.5 m/s
10	1.1 m/s	1. m/s	1. m/s	.5 m/s	.5 m/s	1. m/s	1. m/s	.4 m/s	.4 m/s
Average	1.1 m/s	1. m/s	1. m/s	.5 m/s	.5 m/s	1. m/s	1. m/s	.44 m/s	.45 m/s

Of the 8 tests conducted, only two tests could be tested statistically due to the other six having a standard deviation of 0, which caused a divide by zero error when calculating results.

<u>Differences of Means</u>

Tests	Difference in Air Velocity (m/s)
Control - V1	0.1
Control - V1 cap	0.1
Control - V1 dep	0.6
Control - V1 cap dep	0.6
Control - V2	0.1
Control - V2 cap	0.1
Control - V2 dep	0.66
Control - V2 cap dep	0.65

<u>Confidence Interval (CI)</u>

CI for V2 dep: (0.62306, 0.69694)

CI for V2 cap dep: (0.6123, 0.6877)

The experimenters are 95% confident that the velocity when adding V2 dep decreases between 0.62306 to 0.69694 m/s and our air velocity when adding V2 cap dep decreases between 0.6132 to 0.6877 m/s.

<u>Explanation of Results</u>

Based on these trials, it can be seen that although none of the differences were statistically significant, there was a greater difference between the control and V1 dep, V1 cap dep, V2 dep, and V2 cap dep compared to the differences between the control and the other trials. In further testing, it will be useful to use a more precise anemometer to ensure that the standard deviation and standard error for the trials do not equal 0, hindering the ability to measure what is statistically significant. In addition, it must be guaranteed that in further testing all conditions are met and more trials are conducted for more precise results.

<u>Analysis</u>

This experiment is certainly limitted by the equipment available, as more precise equipment would be able to provide far more accurate results and better distinguish between tests. V1, V1 cap, V2, and V2 cap all yielded the same results for all trials, and these trials could be better analyzed for their more subtle differences with a more precise anemometer that supports graphing on a computer or other device. Also, a better anemometer could allow a conclusion to be drawn as to the effects of valve v1 on air velocity as opposed to valve v2, a conclusion that could not be drawn in these tests.

The presence of a cap on the valve had very little, if any, effect on the measured air velocity. In V1 versus V1 cap, V1 dep versus V1 cap dep, V2 versus V2 cap, and V2 dep versus V2 cap dep, there was a negligible change in air velocity. That being said, this does not necessarily correlate to whether the presence of a cap will have an effect on the tone quality of the instrument.

Depressing a valve had the largest effect on the air velocity of all tests. The average decrease in air velocity when the valve was depressed was 0.63 m/s, which is notable but not statistically significant. As seen in the informal tests, there might be a correlation between the length of pipe that air travels through and air velocity. Given the controls of the experiment, there is definitely a decrease in air velocity once the valve is depressed, although this may change with differing lengths of tubing.

This test does not suggest whether valve v1 or valve v2 has a more optimal design of minimizing change in air speed. Both designs had virtually the same data for each modification onto the valve. However, this test does pose some other questions: is decreasing air speed related to air leakage in the first place? How might one properly test the air leakage in the valve? Does air speed relate at all to the tone quality of the instrument?

Part 5 - Conclusions

Reflection

The overarching goal of this CAPStone research project was to determine how new manufacturing technologies can be used to decrease the cost of musical instruments, particularly honing in on the possible uses of 3D printing in brass instruments. Based on the research, I believe that 3D printing has the capability of being effectively used in brass instruments, although consumer 3D printing has not progressed far enough to be effective for use in critical components of brass instruments.

My research and experimentation were not successful in finding an optimal valve design that would be an effective replacement of a standard tuba valve, minimizing air leakage and rotational friction. Its failure can be linked to several themes: insufficient 3D printing accuracy, insufficient time, and insufficiently accurate measurements of the data. Furthermore, as this experiment progressed, I began to realize that the experiment may not accurately address the air leakage problem.

The experiment devised to minimize air leakage measured air velocity at the end of a length of piping, which was thought of being a good metric of air leakage by comparing the difference of the air velocity between a pipe and a pipe with a valve attached. However, in some preliminary tests, it appeared that air velocity was proportional to the length of pipe that the air traveled through. The air velocity drop would be far more in a 12” length of pipe as opposed to a 3” length of pipe. As such, since the air must travel through extra piping when the valve is depressed, the air velocity may have largely reflected the extra piping as opposed to the air leakage.

The 3D printers used to print the valves (2014 Flashforge Creator Pro) work at creating a valve, however, their print quality is not astounding. For a valve, the tolerances must be minimal so that no air escapes and these 3D printers were not able to provide the amount of precision required. In addition, the print quality was acceptable, but there were artifacts on the valves that prevented them from rotating adequately. This issue may be resolved in modern 3D printers, for example, the Prusa i3, of which I had no access to. It is possible to tweak the print settings such that the issue could be minimized and permit the print quality to be adequate for printing valves. However, it would require several weeks of fine-tuning, and time is another resource that was lacking.

Insufficient time limited many things, among them the number of prototypes that could be designed and tested. This detracted from the quality and validity of the experiment, as two variants of a valve are simply not enough to determine an optimal design for a leak-free valve. With more time, the variations to valves and print processes can be further explored and runners for the most optimal valve design could be determined. Also, a revised experiment that better tests air leakage can be fabricated and better methods of collecting data can be used.

As with many experiments, more accurate instruments can provide better data, and this experiment would have certainly benefitted from a more accurate anemometer. The anemometer used in the experiment could only measure to the tenths place for air velocity, which was an unforeseen problem. Due to this, much of the data had identical results that were not reflective of their actual velocities, and the T-test could not proceed with six of the tests due to no change between all trials. Had the anemometer read into the hundredths place, this problem would not occur and those six tests could be conducted, yielding more results to analyze.

An Optimistic View Forward

Even with the numerous shortcomings of the experiment, I do not wish for more definitive or better results; I certainly learned a lot from this research, definitely more than if the experiment proved everything that I had hoped for. Most importantly, this experiment emphasized that poor results from a terrible experiment still have value. Failure is the first step to success, as determining that air velocity is not a plausible metric for my experiment puts me in a better position for future experiments that pave the road to a functional plastic tuba. Also, over the summer and during college, I will have more time to research alongside with better 3D printers on campus, and these both alleviate some of the constraints of the experiment. Furthermore, the failure of this research drives me to continue researching because I desperately want to turn the plastic tuba into a reality.

I still hold the position that 3D printing is the future. Over time, consumer 3D printers will become cheaper and print better. In RepRap 3D printers, the idea of evolution is always present: if a printer design is problematic and fails, its lineage ends and the most optimal printers continue forward, similar to survival of the fittest. As 3D printing becomes more mainstream, the course of innovation will be the same as the course of evolution, and 3D printers will evolve to be better akin to RepRap printers. Only time will dictate when outrageous ideas can become realities, just like the plastic tuba.