Molding a pneumatic tongue with human-like movement using silicone

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***Abstract*— The goal of this project was to create a Pneumatic Artificial Muscle(PAM) from silicone, that would have some characteristics, mainly movements, of a human tongue. This tongue could one day be used in human-like robots, or as a substitute for someone who has injured their tongue. The project shows that there is potential to make such a tongue, but that it is a hard process, with lots of pitfalls.**

I. INTRODUCTION

Pneumatic Artificial Muscles(PAMs) can be used for a wide variety of applications where mimicking nature is the goal. Anything from mimicking movements from different animals(like fish, caterpillars, octopus and so on) to making muscles that have the characteristics of human body parts. In this project, we are trying to design a tongue from silicone, that could be used with air pressure to achieve similar movements from a human tongue. Our earlier work was performed with a PAM that had a single air chamber, and therefore only could move in one direction, but our goal is to implement several air chambers in a single muscle to be able to get movement in different directions by controlling the air pressure in each chamber. Similar work has been done earlier, but only in simulations, and we wanted to construct the muscle to see it work in practice. The movements we consider when we are trying to duplicate a human tongue is the 4 movements discussed in X. Lu et. al.[1], Roll, Grove, Elongation and Twist.

II. PREVIOUS WORK IN THE FIELD

For many years there has been a lot of research done on the use of Pneumatic Artificial Muscles as muscles for different kinds of robots and to mimic different kinds of animals[6][7][8]. This is mostly because PAMs have many advantages over normal mechanical muscles. They are soft and can be made to fit into many different environments, they are relatively cheap to produce and they can be made into basically any form imaginable. That means they can mimic most types of soft muscles and animals. The reason we bring research on animals into our project is that many of these use 2 or more air pockets to produce the movement they want. Therefore this is related to our work of using multiple air pockets to achieve movement in our tongue. On of the most relevant works is R. K. Katzschmanns et. al.[4] work on a robotic soft fish, gives inspiration for an alternative way of generating movement from side to side, with a silicone muscle. Robin Hofe et. al.[5] have made a model for the entire tongue and vocal tract, but their focus has not been on specific movement on the tongue, it is less relevant. Most relevant for this project is X. Lu et. al.[1], where the concept of a human tongue is described. The goal of this project is to be able to produce the movements they simulated, being Roll, Groove, Elongation and Twist.

III. CRAFTING THE TONGUE

Designing all parts of the molding process was done in Fusion360, which is a CAD program. They where later 3D printed on Ultimakers, mainly Ultimaker 2+ and Ultimaker 3.

A. The main casting mold

The large casting mold was split into 2 parts so that it would be easier to disassemble after the molding process was completed. It was crafted as a male and a female part, which would fit together tight so that we would not have leakage of silicone during the molding process. This method of creating the main casting mold would also make it easier removing the tongue from the mold after it had cured, compared to earlier iterations where we used a solid mold that needed to be crushed in order to remove the tongue. Figure 1 shows the 2 part casting mold.

Fig. 1. The split main casting mold

B. The inlay arms

To create air pockets inside the tongue, we decided to cast arms that was suspended from arms on top of the main casting mold. The thought behind this were to cast them out of another material, that could be removed after the tongue mold was finished. Different materials were tried, mainly pva plastic and Moldlay[3], but because of difficulties getting the material out, we had to rethink the process. We gathered inspiration from [4], which used a wax to create the inner part of a silicone fish. The wax we chose to use was candle wax. The reason we chose candle wax is because of its low melting temperature, how easy it is to acquire, its price and how easy it is to work with. Also, the fact that candle wax does not give off any fumes was important in the choice. A casting mold was printed and metal rods were used as the arms that would suspend the candle wax part. Figure 2 shows the process. These were placed in 3 support beams that would hold them in place while the silicone was poured.

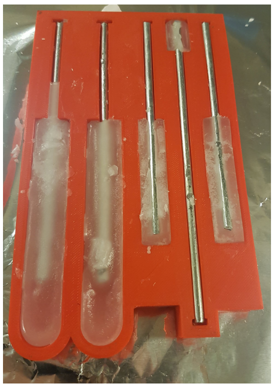

Fig. 2. Inlay arms casting with candle wax

C. The mesh

To be able to transform the movement we want from a straight ahead(from the viewing point of the tongue) to a movement to one of the sides, we mold a cotton mesh into the silicone. The idea behind this mesh is that it will not expand in any direction, but still remain flexible from side to side. So by expanding an air pocket on one side of the mesh, the mesh will restrain movement on 1 side of the air pocket, so that the movement will bend around the mesh.

D. Casting the complete tongue

All parts were then assembled and between the inlay arms, a cotton mesh was put so that it would be cast into the silicone. Elastosil M4601[2] silicone is a 2 part(A and B) silicone that is mixed together. This silicone type is very durable, vulcanizes at room temperature and is very easy to work with, and was chosen for those reasons. After all the parts were assembled, the silicone was poured slowly down from the top. Figure 3 shows how the completed mold looks before silicone is poured in. The entire setup was left to cure for 24 hours.

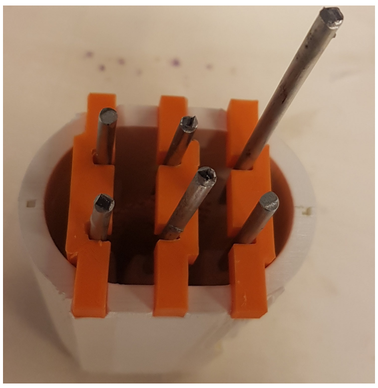

Fig. 3. Fully assembled casting mold

E. Melting the inlay arms

Gloves that could withstand hot wax was used, and a set of pliers used to not come in direct contact with the heated silicone or wax. The candle wax has a melting temperature of 73 degrees, so we chose to use an oven heated to approximately 80 degrees. Underneath the tongue that was placed upside down, we placed a bowl made of tinfoil to catch the candle wax that melted. The whole mold was preheated for 10 minutes in 50 degrees so that the metal bars could easily be pulled out. Then the whole cast was left in the oven for 30 minutes, to assure that all the wax was melted and had exited the mold.

F. Problems that can arise

Air bubbles: Air bubbles are quite devastating for the final product since they will create weak points in the chamber with compressed air. This will cause the tongue to be very fragile to higher air pressure, which again means that we will not be able to get the movement we want from the tongue, without breaking it. The main reason air bobbles form is when the silicone is mixed, and to avoid this we always stirred it very slowly. We also tried to pop all air bobbles we noticed, and was pouring very slowly to avoid forming new bobbles.

Thin walls: Thin walls will also give the finished product a problem with withstanding the pressure that we want to use because it gives us weak points. To battle this we designed all walls that would be supporting air to be at least 5mm thick. Since the process is not entirely the same each time, the thickness of the wall is not consistent. But by using 5mm as our lowest thickness, this will assure that we have some buffer before we get very thin and fragile walls. Misplacement of the inlay arms during the crafting process can also cause thin walls, and many of my tries gave very thin walls that broke right away when they where pressurized.

Time issues: This is a process that takes a lot of time, and if you do not have access to equipment all the time, doing more iterations will consume most of your time. Since most of the tries will be failed attempts, one would need to craft many times to get it right.

To high air pressure: Using to high air pressure on the muscle might cause it to be destroyed. It is therefore important to start with low pressure and work your way up to the pressure you want. There might be inconsistencies with each cast, and that makes it even more important to try lover pressures every time it is tested. Eye protection should always be used since any debris from the casting process might still be inside the muscle and under pressure. In the event of using to high pressure, muscles will explode, sending any debris flying out.

IV. Controlling the Tongue

The tongue has 6 air pockets, so the way it is controlled is by letting air into different pockets movements from the tongue. Some of the movements need air in several of the air pockets to obtain the pose.

A. *Equipment used*

- Large air compressor
- 6mm air tubes
- 12v power supply
- 6 air valves
- Arduino UNO to control the air valves
- Zip ties to secure the air tubes in the tongue
- Wires, buttons and breadboard to set up the Arduino to control the valves with a button press

B. *Setup*

Each valve was set up to a shared air supply from the compressor, and was then connected to the designated air pocket. This way we could individually control each of the valves to give air pressure to the air pocket we wanted. The tongue was secured with a zip tie to hold the air tubes firmly in place. The valves were connected to a 12v power supply and an Arduino, and power was directed through a button so that we could push the buttons we wanted to activate that air pocket.

C. *Improvements*

To be able to better imitate a human tongue we would need to use a setup that could variate what pressure we input to the tongue. Instead of using the valves we use, which could only be turned on and off, we could have used a setup with either a piston controlled by a motor, or a gear pump. Since this was not part of the project, valves would be sufficient.

V. Iterations of the Crafting Process

The entire process turned out to be pretty complicated, and a lot of iterations was made along the way. First attempt was with 5 inlay arms. Figure 2 shows those 5 arms. This setup later showed to be quite unstable, mostly because the walls created, both between them and on the outer part of the tongue, was to thin, and the air would rather expand outwards. Figure 4 shows the setup of mesh around the center inlay in the first iterations. The thought behind this setup was to give a rigid structure in the middle of the tongue, that would not stretch in the forward direction of the tongue. Center inlay was meant to be a tongue tip, that would cause the tip to point upwards. This worked to a certain extent but was later changed to a full sheet of mesh between the top and bottom layers of inlays.

Fig. 4. Mesh placement on the earlier iterations

The main casting mold also had some change. First one started with a 1 piece mold, which then needed to be crushed to retrieve the tongue. Later iterations were made with a split mold. The first iteration also featured a lid that would hold the inlays in place, but this was too complicated, and the placement of beams over the top of the mold was used. To increase inlay number, and also leave space for thicker walls, the main mold was increased. The increases in size are shown in table I and the different iterations are shown in Figure 5.

	Iteration 1	Iteration 2
Width	5cm	6cm
Thickness	3cm	4cm
Depth	13.5cm	14cm

TABLE I

CHANGES IN SIZE OF THE MOLD OVER THE ITERATIONS

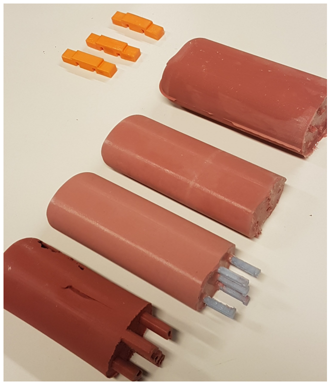

Fig. 5. All the finished casts. The first iteration from the left, until the 4th iteration on the right. Also shows the support beams

Iteration 1: First iteration was made with inlay arms of PVA plastic. The thought was to be able to put the entire muscle in water a couple of days and let the PVA dissolve. An ultrasonic bath was used, and it was left in the bath for 3 days. This proved not to be enough, and there was still very much PVA that was not dissolved after 3 days. The reason why the PVA did not dissolve good enough, was the lack of circulation around the parts. PVA still seems like a good solution if we would be able to guarantee sufficient circulation, either by leaving the tongue submerged for a lot longer time, or design the inlays so that they have an inner tubing that could be used with a pump to circulate the water within the inlay. Iteration 1 was also molded with a top lid, that was designed to keep the inlays in perfect position during the casting process. This lid was later removed since it did not give any improvement over the beam structure we used in later iterations.

Iteration 2: The new idea was to use Moldlay[3] to create the inlays so that they could be melted away after the casting was done. This turned out to be easier in theory than in practice, and since we had problems getting access to an oven that would have the correct temperature and venting of fumes, we decided to move onto the next iteration.

Iteration 3: Inlays was cast from candle wax for the first time, and this gave us the first working model. Of the 5 air chambers, only 3 of them worked initially. The 2 remaining had been to close to each other, so they had merged into

1 chamber with 2 air inlets. After testing on the remaining air chambers, we got decent movement, but the walls seemed very thin and the air created huge bulges on the walls instead of using all its power to create the movement we wanted. After further testing, even 2 more air chambers broke due to air bubbles. Figure 6 shows the movement we achieved from Iteration 3.

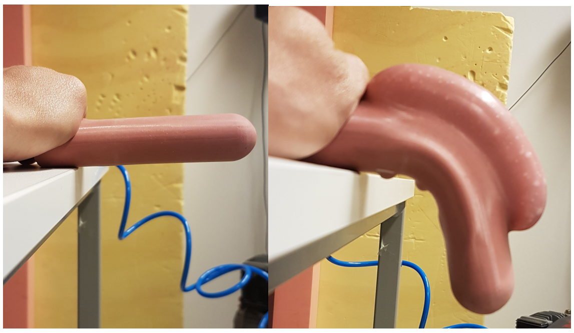

Fig. 6. Showing movement of Iteration 3, with 0 bar pressure (left picture) and aproximately 0.2 bar pressure(rigth picture)

Iteration 4: The last iteration was then designed with thicker walls and was also created with candle wax inlays. With experience from earlier projects, 5mm wall thickness seemed like it would be great to get the movement we wanted. As you can see in figure 5, the last cast was noticeably bulkier than the earlier ones, and this was due to the increased wall thickness.

Fig. 7. Pictures of Iteration 4. Top left shows 0 bar pressure, top right shows approx 1 bar pressure , and bottom picture shows what rotation that was achieved from 1 bar pressure .

VI. CONCLUSIONS

Our goal was to construct a tongue that could show some of the characteristics of a human tongue. Even if we did not manage to reach our goal, we showed that it was possible under the right circumstances and we managed to get good movement. The movement we got was quite large, and with enough time and tries we are fairly certain that we would have been able to produce a functioning tongue. One of the main problems with our approach is how big the air pockets became when they were pressurized. Our third iteration showed very much movement with very little air pressure, and our next iteration showed good movement at around 1 bar. This was expected since we increased the wall thickness. Getting consistent air pockets with no air bobbles showed to be the greatest problem, and that could be fixed with improvement in the casting process. We showed that part of the goal was reached, but there are still improvements to be made.

VII. FURTHER WORK

To improve success for the tongue, we would need to improve the way the whole casting process works. The casting process we used gave to big inconsistencies regarding the thickness of walls and air bubbles. Something would also need to be done with the way the air bubbles blew up on the outer parts of the tongue. This could be done with an outer support structure that only restricted movement outwards, but not stretching. And next iteration was meant to have cotton strings cast into the silicone, to avoid this problem. Some research could also be done on the size of the air pocket. One approach could be to have flat pockets made of a elastic material that would be casted into the mold instead of inlay arm, and it would be interesting to see what kind of movement we could get from this type of approach.

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