3D Printed Underwater Housing[1]

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***Abstract*— 3D printing, or adaptive manufacturing, has become a common tool to use when developing attachments for many different applications. In this paper, the viability of using inexpensive Fused Deposition Modelling 3D printing techniques to develop a housing to hold sensors is explored. The developed housing is not only required to hold the sensors, it also needs to be able to conform within the given predefined mounting points of a commercially acquired robot. The main challenge proposed is the ability for the device to be able to be submerged under the water for extended periods of time while an AUV is completing a variety of tasks**.

***Keywords*— 3D Printing, Additive Manufacturing, Underwater Box, AUV**

I. Introduction

3D printing, or adaptive manufacturing, has become a popular way to cheaply and accurately manufacture components for use in research, hobby and small manufacturing projects. There are many different types of 3D printing devices available, such as relatively cheap models that vary in prince from around $200 - $3000, all the way up to industrial type machines that can be in the tens of thousands up to hundreds of thousands of dollars. 3D printing is not only limited to using plastic, as is presented within this paper, but can also be completed using a variety of different materials such as metal, rubber, etc. Generally the cheaper printers utilize plastic for their material choice due to its ease to work with and low cost to produce. The type of printer used within this paper operates by heating up the plastic until it can be extruded, then placing down layer by layer of plastic until a model is completed, often referred to as fused deposition modelling (FDM)[1-5]. Other Types of 3D printers do exist, such as stereolithography, which essentially uses a resin and UV light to cure the resin into the correct shape [2, 6] or selective laser sintering[7] , but these printers were not used in this experiment due to availability.

There are many advantages of using 3D printing technology over traditional methods to construct equipment. By using 3D printing you can easily design a part one day on a computer using some Computer Aided Design (CAD) software[1, 2, 5, 8], put the part on to print overnight and then retrieve the part in the morning for testing. You are then able to rebuild/refine the module all in the time that it can take to generate the original module by hand, thus allowing for quick development and testing of the artifact[6]. It is also generally cheaper to utilize a 3D printer as the only cost involved is the same material that can be used in a wide variety of projects, with relatively little waist. Little hand skills are also required to generate models as once the part has finished printing, the only post processing that should be required is the removal of that part form the build plate as well as the removal of support material. Because of this ease of use, the designer is not limited by what they are able to accomplish with their own hands and tools, and therefore components can be generated that look aesthetically appealing, can be easily replicated[8] and can easily fit within predefined constraints, such as preexisting mounting points[9]. Because of these major advantages, it was decided to determine if a cheap 3D printer could be used to generate a housing that would be able to hold sensing equipment to improve the functionality of a preexisting robot. To be able to do this the 3D printed part would have to conform to the predefined mounting points already existing on a robot, as well as being able to withstand the constraints that the underwater environment places onto a housing that would not normally exist, these mainly being the pressure that is exerted by water as well as the fact that the water must not be able to reach the sensing equipment.

II. Housing Material

When 3D printing is considered as a construction technique, the material that will be used also needs to be considered. This material, also known as filament, is generally plastic in nature and comes in either the form of Acrylonitrile Butadiene Stryrene (ABS) or Polylactic acid (PLA)[9]. There are many other variations of this plastic available on the market such as metal or wood infused plastic, nylon, etc. With ABS and PLA being the most common, as well as being the base for many of these exotic filaments, PLA and ABS were chosen to use for the construction of the housing.

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A. Polylactic Acid (PLA)

PLA was the first type of material that was trialed. PLA is generally considered the easier of the two materials to print with, as it is not as sensitive to changes in its environment while it is printing, making it much easier to print with. PLA is generally considered more brittle than ABS, which can be considered a large downfall as the constructed artifact will need to withstand an increased pressure from the surrounding environment, as well as any accidental collisions that the robot might endure. The finial downside to PLA is that due to it being Bio-degradable, it also has the ability to absorb water. As shown in [10], after a period of time this absorption of water can significantly reduce the strength of the artifact. This makes it not ideal for this application, but can be avoided by applying a coating over the top of the plastic to prevent it having contact with the surrounding water.

B. Acrylonitrile Butadine Stryene (ABS)

ABS has many advantages over PLA. It is a significantly stronger material, therefore ensuring that it will be able to withstand harsher conditions such as the pressure and collisions that the robot might occur. Unlike PLA, ABS also does not absorb water at all. This means that a coating does not have to be applied to the outside of the box to make it water resistant. Another advantage of ABS is that it can easily be smoothed by applying a coat of acetone to its surface. In the case of the proposed application, this not only smooths the surface of the part, but also fills in the tiny holes that are present during the printing process when the FDM technique is use. If these holes between the layers are not filed in, the box could potentially leak through the sides, if enough pressure is applied. It is much harder to achieve the same result with PLA.

C. ABS vs PLA

As shown in section 2.1 and 2.2, there are many differences between ABS and PLA. For the use in this project, the main difference that was considered is whether or not the material is able to withstand the pressure that the water will exert into the box and how much post processing needs to be done to the material to ensure that it will be able to prevent leaks in an underwater environment. Taking this into account, it was decided that ABS would be the preferable material, as it is naturally waterproof, unlike PLA, and should be able to last significantly longer without having to be reprinted.

III. Seal Material

As well as choosing a material for the housing to be made out of, it is also important that a material for the seal is to be chosen as well. There are many different types of materials that can be used as seals for waterproofing equipment. Most of these materials are either made up of rubber, silicon or foam. Waterproof seals also come in many different forms, with the most common being a flat seal, O-ring and a gasket. For the construction of the housing, the flat seal and the O-ring were mainly considered.

A flat seal consists of getting a single piece of waterproof material, such as rubber, and placing it around the surface that is to be the seal. This material is then evenly compressed and thus the water is unable to get passed the barrier. It was determined that the construction of a flat seal would be difficult the more completed the shape of the seal. Due to this, and the ability for a 3D printer to effectively print a seal in any shape that the user desired, a flat seal was not considered the desired option.

An O-ring was chosen as this seemed to be the standard way of waterproofing equipment, and has been used to waterproof other underwater artifacts[7, 11]. It is easy to make an O-ring into custom shapes that can be generated with 3D printing as long as the seal is continuous. This is due to the material coming in a single strip that can be cut to the correct length and then the ends fused together without the material ever having the issue of being bunched up and crinkled which would enable the water to get through. An O-ring operates in much the same way as a flat seal, as compression enables the gap between the lid and the body of the equipment to only be filled with the O-ring material, and therefore no water is able to pass through.

Four different types of material were used for testing. The first was some cheap foam O-ring material that came with a hobby box. This material was very compressible and easy to mount to the housing.

The second material that was trialed was some rubber sheeting found at Home Depo. This was the first material that was trialed for the use as a flat seal. This material was very hard to compress.

The third type of material that was trailed was 3mm Buna O-ring material. This material had a duro rating of 70, and is widely used to waterproof various forms of equipment. Having a rating of 70 duro meant that this material could be compressed by hand, but it required a significant amount of effort.

The finial material that was trialed was 3 inch Tank-to-bowl gasket for American Standard Cadet 3 Toilets. This material was trialed as both a flat seal and a gasket. This material was very easy to compress by hand. The results that were obtained using these materials are described in section 4 and 5.

IV. Housing Construction

3D printing can be used to make many different artifacts, such as brackets and gears, that will either increase the functionality of an object, such as a robot, or to replace inefficient or broken parts. It was decided that 3D printing would be used to construct an attachment for an underwater robot that will enable the robot to interface with modern sensors, such as an IMU, thus enabling the robot complete more sophisticated autonomous tasks. The advantages of 3D printing are that the housing can be designed in such a way that it would have only a small impact on how the robot traveled through the water, as it could be designed with aerodynamics in mind. It also allows the ability to design the housing so that it can easily mounted to the preexisting points on the robot, in this case the VideoRay Pro 3, with minimal interference as to how the robot currently operates as it will not get in the way of any existing equipment, such as thrusters. Another advantage of utilizing this technique for construction is if more room was required for various reasons, such as increased sensing capabilities or the inclusion of an onboard power source, the design could easily be modified to accommodate.

When constructing a container to house sensors you need to consider how hard it will be to get to and maintain these the various sensors and equipment that the housing contains. When the container is placed onto a vehicle that will be traveling through the air, the problem becomes more complicated as the vessel not only needs to be able to be easy to get to, but it also shouldn't hinder the craft in anyway, therefore the aerodynamics of the housing as well as the weight of the sensors and the housing needs to be considered during design and construction. The same problem becomes even more complicated under the surface of the water, as not only the weight and aerodynamics of the vessel should be considered, but also whether or not the vessel will be water proof and how buoyant the vessel needs to be to enable the vehicle to easily submerge and raise again, all being a major factor going into the design process. Each of these metrics were taken into consideration during the design phase of the underwater housing, and will be described alongside each of the construction stages.

The sensors that the box was required to carry was an BNO055 Inertial Measurement Unit (IMU) to enable the pitch, roll and yaw of the robot to be obtained, an Arduino Mega 2560 to send the information back to the computer, 48V – 50V DC-DC converter to power both the IMU and the Arduino and a cable that allows the power to be drawn from the robot as well as enabling serial commands to be sent back to a computer.

The first version of the constructed housing tried to take into account all of the design metrics listed, and is shown as a computer model in figure 1, and as the actual artifact in figure 2. Initially this box was constructed out of PLA instead of ABS, as at the time of construction the 3D printer available was only able to use this type material. Three things can be taken out of this design. First of all the lid was slopped down towards the front of the box. This was done for two reasons, to try and make the box glide more efficiently through the water and also to try to keep the amount of air that is contained within the box to a minimum, as the place where the IMU is mounted is higher than the top of the power converter. The reasoning behind this is that with less air in the container, the buoyancy of the container drops. As neutral buoyancy is being aimed for, this is a major advantage. The bottom of the container is required to fit within grooves on a foam floater that is located on-top of the robot, and fastened with a wingnut already present on the robot, thus not restricting the movement of the robot at all. The material used for the O-ring is the first material mentioned in section 3. This design did not function well, as the water leaked though the seal around the top of the robot when submerged to a depth of about 70cm.

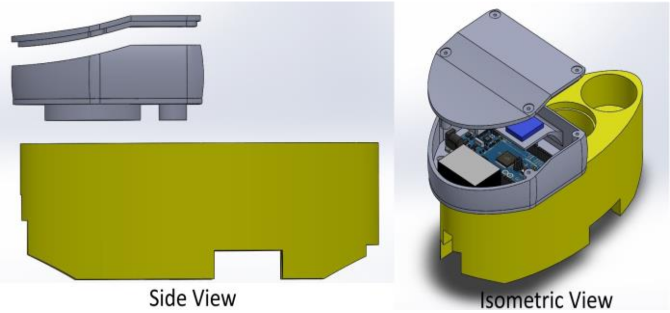

Figure 2 : CAD model of original design

Figure 2 : Original Design

After the construction of the first box, it was discovered that PLA has the ability to absorb water, as demonstrated in [10], and therefore was not the best material choice for underwater applications. To overcome this, the box was then coated in silicone. 100% silicone sealant was used, as this material is cheap as it can be brought from any hardware store and is very easy to apply. This fixed the problem of the PLA being able to absorb the water, as no PLA was exposed to the water any more. The main disadvantage to this method is that if the box is involved in a collision, the coating could potentially be damaged and therefore the PLA becomes exposed again. Another screw hole was also added to the front of the housing, to try and achieve increased and consistent pressure throughout the seal, as shown in figure 3. The seal was also siliconed into place to try and prevent the O-ring from moving anywhere during tightening of the screws onto the seal. Again this seal functioned well when placed just under the water, but failed at a depth of 70cm.

For the construction of the third box, a printer that was able to print in ABS was made available, and therefore PLA was abandoned for ABS. The main reasoning behind the move was that ABS was naturally waterproof, and ABS could also be smoothed using acetone to remove the gaps that exists between the individual layers that are introduced while utilizing this printing process, something that is very hard to replicate with PLA. Two more additions were added to this design, one of these being a 1.5mm groove for the 3mm O-ring

Figure 3 : Revision 1

to sit in so that the silicone would not have to be compressed along with the O-ring, as well as the spots for metal nuts to sit that the screws can screw into, thus enabling more compression when screwing down the lid. More compression is achieved as it is much easier to strip threaded plastic than it is to strip a metal nut, thus loosing compression. This stripping of the plastic is demonstrated as the screws become loose to tighten after they have been screwed and unscrewed multiple times, where this problem is not present when metal nuts are introduced. Figure 4 shows the implementation of this design. The first flat seal was also tested with this design, this seal being made out of the second material described in section 3. This material was found to be too hard to achieve compression without flexing the lid of the container. Again this, and all subsequent tests was successful when placed just under the surface of the water, but failed at a depth of 70cm over a period of 1 hour.

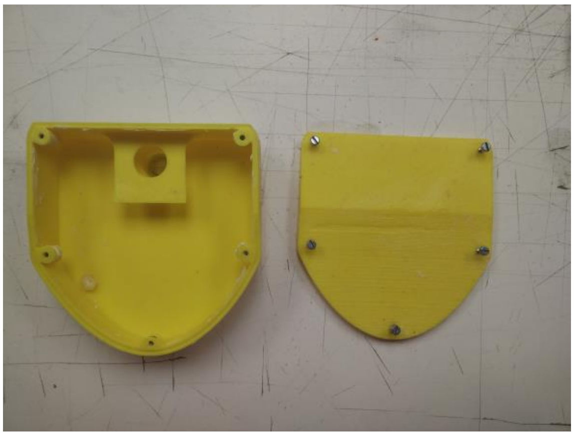

Figure 4 : Revision 2

During the testing phase of the previous design, it was noticed that the compression along the curve was not as great as it was during the flat parts of the box, causing leaks at these points. To overcome this, the next iteration of the box removed the curve completely. It was stated that the aerodynamics of the box and buoyancy needed to be taken into account, and by removing the slant on the lid is going against these initial metrics. To try and keep within these guide lines, the curve at the front of the box and along the edges was maintained to reduce the drag that the box would have on the system. It was decided that the buoyancy issue could be overcome by adding weights to the inside of the box, thus being able to get the box to the neutral buoyancy that is required. The screw holes were also moved from the inside of the box to the outside. This was done for two reasons. First being that the area that needed to be sealed was now smaller as the places for the screw holes did not need to considered anymore. It also reduces the potential for possible leaks as the screw's themselves now do not pose a threat to the seal. For the same reasons, the holes where the wing nut sits to mount the device to the robot has also been moved outside of the box. The results are shown in figure 5. It can also be noted that the lid for this iteration of the box has warped during testing. The lid is constructed out of 3mm ABS plastic, and it was found that at this thickness a combination of the compression of the screws and the pressure of the water was enough to cause the lid to bow in the middle, and therefore not provide a good compression onto the O-ring, causing the seal to be able to be breached by the water. It should also be noted that the amount of compression points provide by the screws increased from five to nine. This was done to try and get a more even compression around the box, as it was determined that the single screw at the front of the curve was insufficient pressure at that point.

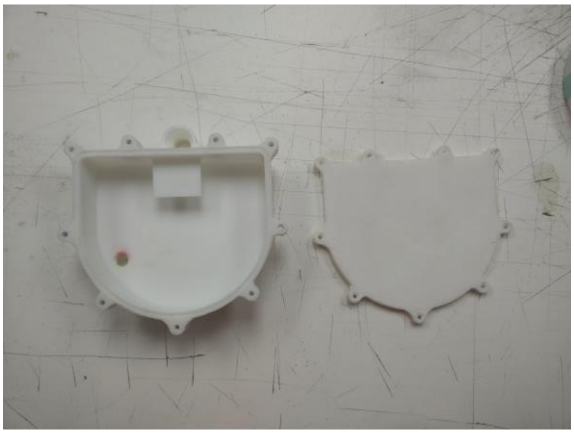

Figure 5 : Revision 3

In the next iteration of the housing, as shown in figure 6, two major changes have been made. The first change that was introduced is to do with the lid. As described above, the previous design of the lid bowed in the middle when under pressure. To overcome this, the thickness of the lid was increased from 3mm to 5mm at the edges, and a 5.5mm curve was added to the top of the lid. This improved the lid as the bending and warping issue that was present in the previous design was not present anymore. The outside of both the lid and the box went through a three stage process to ensure that it is water tight. As mentioned in section 2, ABS does not absorb water naturally. Unfortunately, due to the 3D printing process it might be possible for the water to get in-between the individual layers of the plastic that are generated when whilst the part is being printed. To overcome this issue, three different post processing processes were undertaken. First, the outside of the artifact was rubbed down with acetone. This causes the outside layers of ABS to melt and fuse together, filling in all of these gaps. To make 100% shore the no more gaps were present that water would be able to get into, the casing was also sprayed with liquid rubber, commonly used to seal leaks in gutters, before finally being coated with an acrylic based spray paint. The grove that was holding the seal was also depend so that it was 5.5mm deep. This forced the O-ring to stay in-place as the walls stopped any ability for the O-ring to move around. So that compression could still be obtained onto the O-ring, an extrusion was added to the bottom of the lid that was able to press down onto the O-ring and cause compression. Two different lids were produced, one that would compress the O-ring by 0.5mm, and one that would compress the O-ring by 1.5mm. These extruded components, along with the screws, also ensured that the lid sits in exactly the right position relative to the O-ring. It was found that even with these precautions, a perfect seal was still not achieved.

Figure 6 : Revision 4

After closer inspection to what exactly was happening, it was discovered that instead of compressing the material completely, the flanges on the side of the box that were holding the screws were flexing up to meet the lid, thus not causing a good amount of compression as most of the force was taken up by this flex. The flexing of the material was also causing minor cracks on the surface of the container, which would eventually lead to a failure in the box, and would also allow water to get into the cracks in the side of the container and sit in between the layers of the print, and therefore eventually cause a leak. To overcome this the next design removed the flanges to prevent any of this flexing to occur. As can also be seen in figure 7, enough space was also left so that a flat seal could be included along with the O-ring, to try and enable the use of a double seal, therefore both seals would have to leak to cause there to be a leak in the actual system. The amount of compression points, or screws, was also increased from nine to twenty. The same theory was applied as to why the compression points were increased, to try and get more even compression along the O-ring. It was determined that by adding anymore screws than the aforementioned twenty would not achieve anything new. The meal nuts were also moved to the bottom of the container, so that the added benefits from the nuts would be included in this design as well. This design was tested in four different ways. First, just the use of the initial O-ring material was trialed, with no good results. It was then trialed with both the O-ring and a flat seal made out of the fourth material described in section 3. Again the box seal was still breached, but at a much slower rate than that of just the O-ring. Because of this, a seal was generated by cutting up the material used for the flat seal into a long thick strip, removing the O-ring out of the groove and placing this material in the groove in its place. This was very successful, and no leaks were recorded. The main drawback from this method is that the amount of compression that was required to makes this material entirely water proof broke the inside grove off from within the box. Even though it was considered successful, it was determined that by using this material, the inside wall of the channel in the container would have to be so thick that it would become impractically large to use in operation. The other thing that can be noted between this design and the previous one is the lack of an acrylic coating. It was determined that by simply using acetone to seal the edges was sufficient for the test preformed to determine whether or not the seal would be water proof. If the design was successful, both the rubber and the acrylic paint would have been added ensure water tightness of the casing.

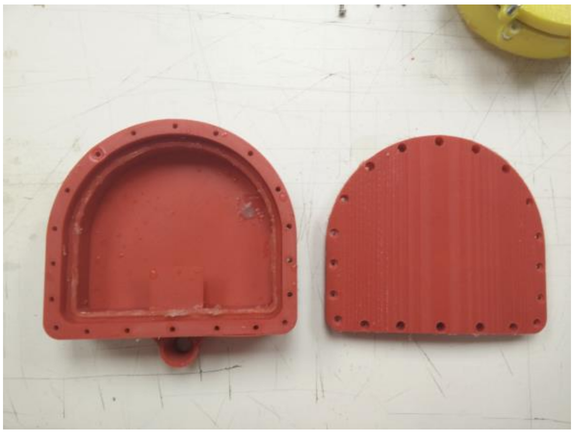

Figure 7 : Revision 5

V. Resaults and Future Work

As described in section 4, an underwater 3D printed housing was unable to be practically constructed, using the chosen materials. It was shown that various things need to be taken into consideration when using the FDM 3D printing method, such as the fact that the a 3D printed part will flex much easier than that of a part made out of other materials, such as injection molded plastic, Perspex, etc. It is assumed that this flexing of the material was the main reasoning behind the parts failing. It was also shown that while an entirely waterproof seal was able to be generated, the compression required to do so was able to break the housing, meaning that it was only able to be tested on a single occasion. It is concluded that to be able to achieve this goal, a material that is able to be compressed relativity easily and still be able to withstand the conditions that are present when underwater, such as significant pressure increase and changes in temperature would have to be sourced, that would also not break the constructed housing whilst under significant compression.

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