DESIGN FOR MANUFACTURING WITH RAPID PROTOTYPING

by

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Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

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(AP DR AHMAD MAJDI BIN A RANI)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
September 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(NASIRUDDIN ZHARIFF BIN RASIP)

ABSTRACT

Design and fabrication of an object with parts embedded internally within a part has always been a difficult challenge to fabricate. This is mainly due to limitations in design for manufacturing (DFM). The main purpose of this project is to investigate improvements in overcoming limitations in DFM of non-metallic object with embedded part within a part through 3D printing technology and Silicone Rubber (SR). 3D printing technology is a type of Rapid Prototyping (RP) method and has limitations in its material, where the product is fragile, brittle and has high failure rate. This technology combined with SR are envisioned capable to overcome some of the limitations as highlighted in DFM without reducing the strength or increasing the failure rate of its product. In this project, the 3D printing technology will be used to construct a scaffolding for the product and SR will be used as material to fill into it. The end product is a unique “One-piece” outdoor water-feature that has absolutely no assembly of parts between its various internal and external components that entraps a free rotating ball feature inside the Water Feature Cage., while having the ductile property and lower failure rate advantage of silicone rubber.. In conclusion, it is expected that this end product will be able to create a new branch in Mechanical Engineering towards arts and aesthetic, which perhaps will create a new revolution for mankind.

ACKNOWLEDGEMENTS

بِسْمِ اللَّهِ الرَّحْمَٰنِ الرَّحِيمِ

In the name of Allah, the Most Gracious, the Most Merciful. All praise be to Allah S.W.T and may peace and blessings be upon His Messenger – Prophet Muhammad S.A.W and his family as well as his companions.

I want to express mu utmost gratitude to Universiti Teknologi PETRONAS for allowing me to complete this project, providing facilities to me to complete this project. I also would like to take this opportunity to direct my utmost indebtedness to my Final Year Project supervisor, Dr Ahmad Majdi Bin A Rani for his prized supervision and advices throughout the entire project. His provisions, tolerance and willingness to assist me in the problem or complications that I confronted in my project have contributed tremendously to my project. His ideas and moral supports that make the project a success to achieve its objectives. I would also like to take this opportunity to acknowledge the Final Year Project coordinator, Dr Azmi Bin Abd Wahab for his effort in guaranteeing the project is developed smoothly within the time frame specified. I also would like to say a big "thank you" to Mr Zamil Bin Khairuddin and Miss Siti Nooriza Binti Abdul Razak for their help throughout this project especially in the laboratory works. Without them, this project would have never been completed and successful. Words alone is not enough to show my gratitude to them. Last but not least, I would like to give my utmost gratitude and appreciation to my family and fellow friends who provide a lot of helps during conducting experiments, helps with software and other essential thing. With their provision and inspiration, this project was accomplished successfully.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLE

CHAPTER 1: INTRODUCTION

1.1 PROJECT BACKGROUND

Prototyping or model making is one of the important steps to finalize a product design. Before the start of full production, a prototype is usually fabricated and tested. Manual prototyping by skilled craftsman has been an old practice for many centuries. Second phase of prototyping started around 1970s when a soft prototype modelled by 3D curves and surface could be stressed in visual world, simulated and tested with exact material. The last trend of prototyping, Rapid Prototyping (RP) originated around early 1980s with the appearance of the stereolithography system. This and then brand new process made a very large impact on the design community, particularly in Design for Manufacturing (DMF). It was based on 3D Computer Aided Design (CAD).

The RP process involved in this project is the 3D printing. There are a variety of methods to accomplish 3D printing, but as stated by Pandey (2004), generally it is done in layers as in Layer Manufacturing Technology (LMT). Layers of fine powder are deposited onto the blossoming prototype, followed in turn by a layer of liquid binder. Once an object has been printed, it can be coated with sealant to strengthen it. Also, many of the machine's components are similar to those in regular printers, but that is where the technologies diverge.

As defined by Pam (2012), Silicone Rubber (SR) is a manmade product derived from natural products – silicone and rubber. It is made by curing or vulcanizing natural rubber. In this project, the author intend to combine RP and SR technologies where the 3D printing technology will be used to construct a scaffolding for the product and SR will be used as material to fill the scaffolding. Combination of both technology are envisioned capable to overcome some of the limitations in DFM without reducing the strength or increasing the failure rate of its product.

1.2 PROBLEM STATEMENT

Design and fabrication of an object, whether metal or non-metal, with parts embedded internally within a part has always been a difficult challenge to fabricate. This is due to limitations in DFM. As stated by Excell and Nathan (2010), RP technology has the ability to construct complex design. Hence, it has the potential to overcome this limitation. However, according to Freedman (2011), the availability of material for this technology is very limited and the strength of the available material is also limited. Besides, according to Freedman (2011), the product from RP has a high failure rate. Prototyping with SR is envisaged capable of overcoming some of the limitations as highlighted in DFM, as well as the limitations of RP.

A liquid-based material which solidifies and grow stronger over time is necessary to overcome the limitations in RP, where in this project, SR is the highlighted material, which react with hardener to cure and solidify. However, complicated structure will still be difficult to be formed with SR. Hence, this is where the advantage of RP technology comes into hand.

Mechanical engineering department had developed a lot of branches throughout its history. This includes mechatronic and bio-mechanical engineering which has contributed a lot towards mankind. However, there has not yet exist any branch towards art and aesthetic. This project is expected to create a new branch in mechanical engineering towards that.

1.3 OBJECTIVES

The main objective of this project is to investigate the improvement in overcoming the limitations in DFM of non-metallic objective embedded within a part through design and 3D prototyping with SR.

Next, this project also aims to overcome the limitations in RP, including the weak strength and high failure rate of RP product and increasing the variety of materials available for RP.

Thirdly, this project is to come out with a physical prototype from the combination of RP technology and SR.

Lastly, the objective of this project is to create a new branch in Mechanical Engineering towards arts and aesthetic. This perhaps will create a new revolution in mechanical engineering.

1.4 SCOPE OF STUDY

Throughout the project, the scope of study will focus on designing a product with a part embedded internally within a part. The design will be manufactured as a scaffolding with a 3D printer. Therefore, flowability test need to be done to ensure the SR will be able to flow throughout the whole scaffolding. Next, strength test will be done to ensure the material does not break when applied an amount of force. Finally with the material selected, the result will be presented in form of a functional prototype made based on the design. The result will be a product with a part embedded within a part feature while having the ductile property and lower failure rate advantage of SR.

1.5 SIGNIFICANCE OF PROJECT

The study of Rapid Prototyping is important to the engineering world. This is because as stated by Hague (cited by Freedman, 2011), with RP, an engineer will be able to have more freedom in design. Besides, with the limitations of RP are overcame, mankind will be able to benefit more from RP technology. As a result, complex designs can be manufactured, and the products being stronger, sturdier and have a low failure rate. Lastly, perhaps a new mechanical engineering branch towards esthetic will develop from this project.

CHAPTER 2: LITERATURE REVIEW

2.1 BASIC PRINCIPLES OF RAPID PROTOTYPING

Prototyping is typically an iterative process, in which a series of products will be designed, constructed, and tested to progressively refine the final design (Nguyen and Vai, 2010). It is thus essential to minimize the latency of each prototyping cycle so that projects adhere to the original design schedules.

In case for RP, many authors do use very limited definition of RP, and only include technologies that build a prototype by stacking numerous thin layers like the original stereolithography system. For instance, Levy defined RP such that it is also referred as layer manufacturing (Levy et al., 2003) and Paul defined RP as the process of building prototypes in slices using layered approach (Paul and Anand, 2011). However, the author agrees more on Lennings, who state that two fundamentally different methods currently available for RP are Layered Manufacturing Technology (LMT) and CNC milling. According to Lennings, RP is a process that automatically creates a physique prototype from a 3D CAD model, in a short period of time. (Lennings, 1997).

However most RP process belongs to the LMT, or known as generative or additive production process, unlike subtractive or forming process, where form is shaped by material removal or plastic decomposition. The parts is fabricated two dimensionally by deposition of layers contoured in (x-y) plane. Single layers being stacked up on top of each other are what resulted in the third dimension (z), but not as continuous z-coordinate (Pandey, 2004). Typical process chain of various RP system is shown in Figure 1.

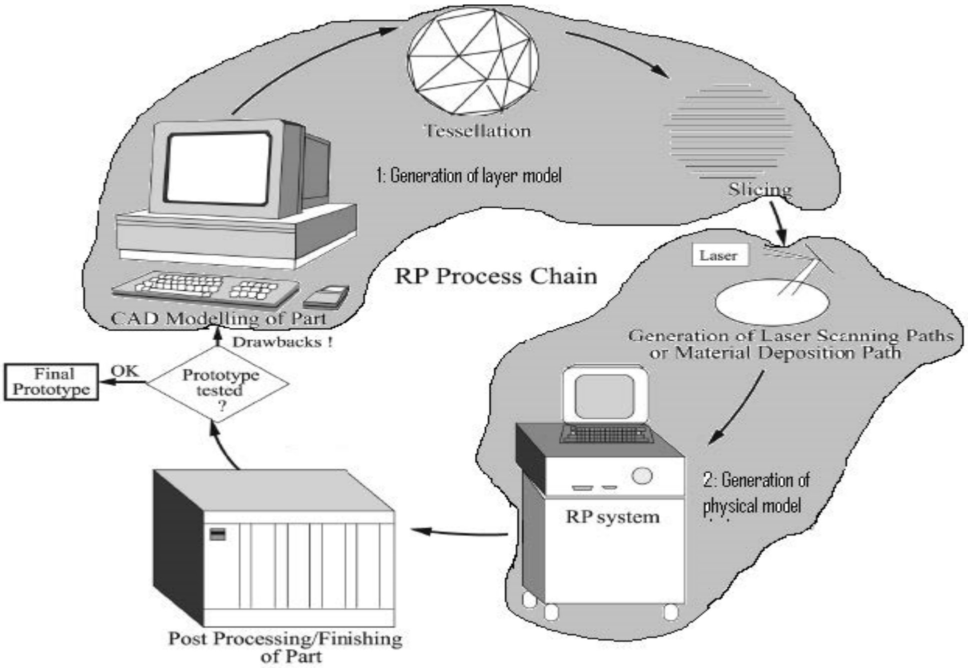


Figure 1. RP process chain (after Pandey, 2004).

Based on Figure 1, before any construction of a component, it is necessary to prepare the control instructions (part program) of the RP system. The approach to prepare control instruction of RP systems involves 3 steps. The first one is preparing the geometric modeling. This consists of modeling the component on a CAD system to define its enclosed volume. Solid modeling is the preferred technique because it provides a complete and unambiguous mathematical representation of the geometry. For RP, the important issue is to distinguish the interior mass of the part from its exterior, and solid modeling provides for this distinction (Groover, 2009).

The next approach is the tessellation of the geometric model. In this step the CAD model is converted into a format that approximates its surfaces by facets (triangles or polygons). More generally, tessellation involves the laying out or creation of mosaic. In the case of RP, the tiles (facets) are used to define the surface, at least approximately. The triangles or polygons have their vertices arranged to distinguish the object’s interior from its exterior (Groover, 2009). The common tessellation format used in RP is STL, which has become the de facto standard input format for nearly all RP systems (Ashley, 1995).

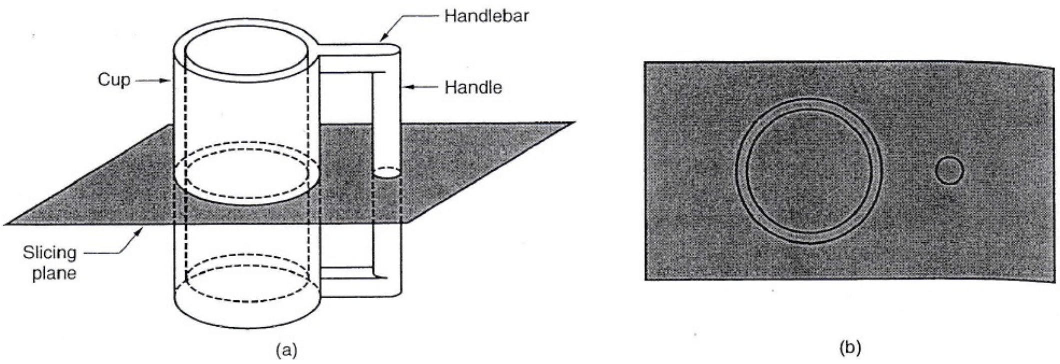


Figure 2. Conversion of a solid model of an object into layers (after Groover, 2009).

Lastly is the slicing of the model into layers. In this step, the model in STL file format is sliced closely spaced parallel horizontal layers. Conversion of a solid model into layers is illustrated in Figure 2. These layers are subsequently used by the RP system to construct the physical model. By convention, the layering procedure occurs in the z-axis direction (Groover, 2009).

Then only the information is used to move to stage 2, where the steps are different for different process and basic deposition principle used in the RP machine. The RP system platform will create the parts layer by layer. Finally the last stage is the post-processing task such as cleaning and finishing (Pandey, 2004).

2.2 RAPID PROTOTYPING PROCESS

The professional literature in RP contains different ways of classifying RP process. However, based on German standard of production process classifies RP according to state of aggregation of their original material (Pandey 2004). The representation is as shown in Figure 2.

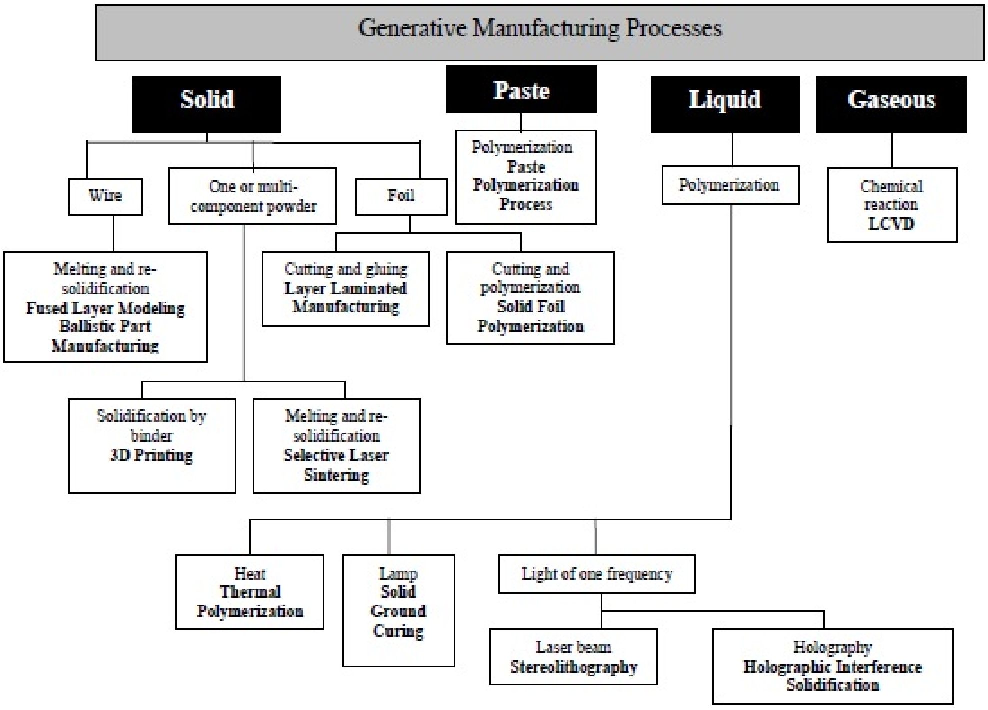


Figure 3. Classification of RP processes (after Gephardt, 2003).

Three dimensional printing build the parts layer by layer fashion using an inkjet printer to eject and adhesive bonding material onto successive layers of powders. The binder is deposited in areas corresponding to the cross sections of the solid part, as determined by slicing the CAD geometric model into layers. The binder holds the powders together to form the solid part, while the unbounded powders remain loose to be removed later. While the loose powders are in place during the build process, they provide support for overhanging and fragile features of the part. The part built on the platform whose level is controlled by a piston. (Groover, 2009).

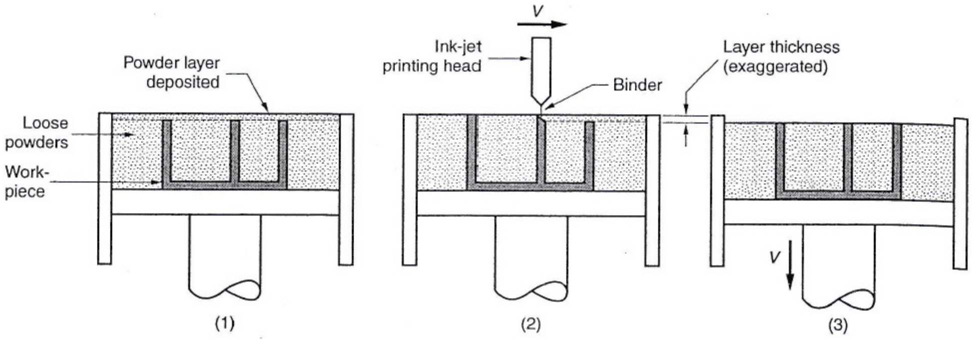


Figure 4. 3D printing process (after Groover, 2009).

With reference to Figure 4; (1) A layer of powder is spread on the existing part in process, (2) An inkjet printing head moves across the surface, ejecting droplets of binder on those regions that are to become solid part and (3) When the layer printing of the current level is completed, the piston lowers the platform for the next layer (Groover, 2009).

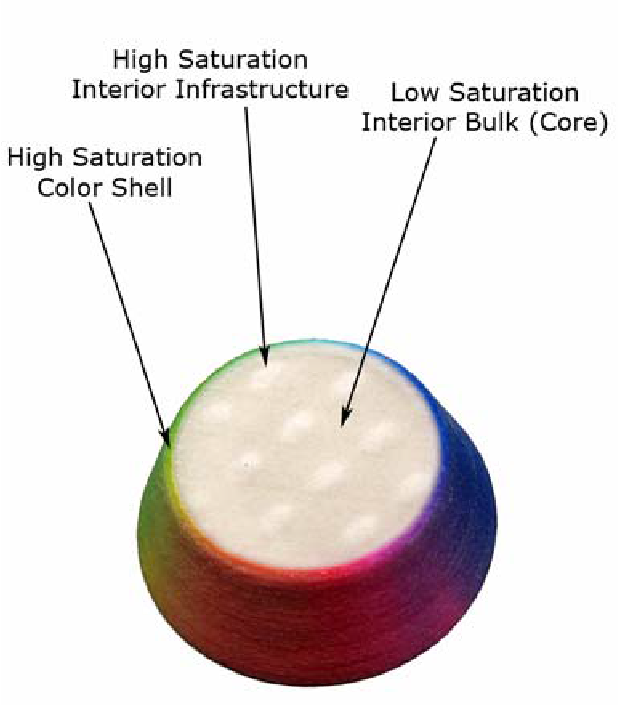


Figure 5. 3D Printer printing shell (after ZPrinter 450 Hardware Manual, 2008).

Each layer is made up of shells. Based on Figure 5, during printing, binder is first applied with a higher saturation to the edges of the part, creating a strong "shell" for the exterior part. Next, an infrastructure that works like strong scaffolding is created for the part walls, which are also built with a higher saturation of binder for added strength. The remaining interior areas are printed with a lower binder saturation, which gives the part its stability. ("ZPrinter 450 Hardware Manual," 2008).

When the part is finished printing, the printer heats up to the appropriate temperature and dries the part while it is still in the Build Bed surrounded by powder. When the drying cycle is finished, an automatic powder removal cycle empties the Build Bed of most of the excess powder around the part, and returns that powder to the Feeder for reuse. After the bulk of the powder removed, the part is moved from the Build Bed to the integrated Fine-Powder Removal Chamber where any remaining powder is cleaned off the part. After the part is powder-free, it is ready to be removed from the printer. The part can be evaluated as it is, another choice is to post-process the part with infiltration products to give it additional strength, durability, and color vibrancy. With the finished part in hands, designers can start improving or modifying your design within the same day, and usually within hours" ("ZPrinter 450 Hardware Manual," 2008).

2.3 ADVANTAGES AND LIMITATIONS OF RAPID PROTOTYPING

RP have a number of advantages compared with the conventional manufacturing techniques. Unlike the traditional subtractive manufacturing, which can leave up to 90 percent of the raw material before arriving at a finished product (Freedman, 2011), RP can significantly reduce waste from traditional machining methods, depending on the materials involved (Shiller, 2013).

Besides, RP is also able to build complex mind-boggling geometrical complexity models from scratch (Excell and Nathan, 2010). It can build arbitrary complicated 3D-physical parts using a general machine, without special fixtures or tools (Yongnian et al., 2009). However, according to Hague, the most competitive advantage of all, is the almost limitless freedom the technology gives to designers.

> *"It frees you from the constraints of traditional manufacturing process. It changes the kind of products you can make and the way you design things. You can make very, very complicated geometries. It's almost as close to Nirvana as you're ever going to get"*
>
> Prof Richard Hague, AMRG (cited by Freedman, 2011)

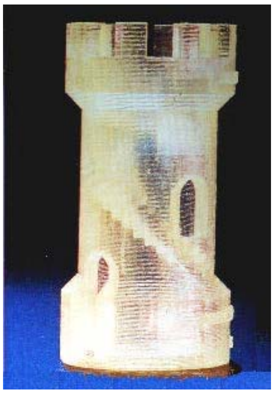


Figure 6. Chess tower (after Lennings, 1997).

Figure 6 shows a chess tower, manufactured by Stereolithography, which is an example of a geometry that cannot be created by conventional manufacturing techniques. Note the staircase inside the hollow chess tower, which inspired the idea of part embedded inside a part concept of this project.

Meanwhile, by using RP to corrugate the insides of some parts can reduce their weight by up to 70 percent, which can save an airline millions of gallons of fuel every year (Freedman, 2011). As quoted by Freeman (2011), Rockstroh says “We’re going on a major weight-reduction scavenger hunt next year”. Besides that, the Unviversity of Louisville’s Gornet notes that RP process could cut the weight of valves, pistons and fuel injectors by at least half (Freedman, 2011).

RP also does not need any assembly. Traditional manufacturing requires assembling many parts, however, RP can fabricate fully assembled final products, reducing labour, global supply chains, and freight costs (Shiller, 2013).

However, RP have some limitations, which stops this technology from being used more broadly (Singhal et al., 2005). Firstly is the bad part finishing and is primarily due to the staircase effect between layers. In all commercial RP processes, the part is fabricated by deposition of layers contoured in a (x-y) plane two dimensionally. The third dimension (z) results from single layers being stacked up on top of each other, but not as a continuous z-coordinate. Therefore, the prototypes are very exact on the x-y plane but have stair-stepping effect in z-direction (Pandey, 2004).

Besides that, Todd Grimm, who heads an additive manufacturing consultancy in Edgewood, Kentucky, estimates that the time it takes to produce a part will need to be reduced as much as hundredfold if 3D printing is to complete directly with conventional manufacturing techniques (Freedman, 2011).

Another limitation of the common rapid prototyping techniques is the narrow choice of materials the prototype can be made of (Czyz˙ewski, 2009). Currently, only a handful of plastics and metal compound is available for RP (Freedman, 2011).

The limited variety of material also leads to limited mechanical performance of the RP prototypes. Generally the materials used in RP systems are not as strong as the production part materials that will be used in the actual product. Thus, this limit the mechanical performance of the prototypes (Chua, Leong and Lim, 2010).

The worst of all, the part from RP is made out of thousands of layer, and each layer is a potential failure mode (Freedman, 2011). The author assumed the failure mode of the layers are in series, which means if any of the layer fails, the part will fails. The failure rate of the part will be the total sum of failure rate of all the layers in the part which can be defined with the formula:

$$\lambda_T = \lambda_1 + \lambda_2 + \lambda_3 + \ldots + \lambda_n$$

Thus, the author concluded that the part from RP have a high failure rate.

Lastly, RP also has a low repeatability. Manufacturers have yet enough data to predict exactly how part will turn out and how it will hold up, or how production variables affect the results (Freedman, 2011).

> *"3D printing often ends up being a black art. A part is made out of thousands of layer, and each layer is a potential failure mode. We still don't understand why a part comes out slightly differently on one machine than it does on another, or even on the same machine on a different day."*
>
> Singh (cited by Freedman, 2011)

2.4 APPLICATIONS OF RAPID PROTOTYPING

Applications of rapid prototyping can be classified into three categories which are (1) design, (2) engineering analysis and planning, and (3) tooling and manufacturing (Chua, Leong and Lim, 2010).

2.4.1 Design

Design application were the initial application emphasis for RP systems, and most of the early applications were in design. Designers are able to confirm their design by building a real physical model in minimum time using rapid prototyping. The features and functions of the part can be communicated to others more easily using a physical model than by a paper drawing or displaying it on CAD system monitor (Chua, Leong and Lim, 2010).

2.4.2 Engineering Analysis and Planning

The existence of an RP-fabricated part allows for certain types of engineering analysis and planning activities to be accomplished that would be more difficult without the physical entity. This includes, (1) comparison of different shapes and styles to optimize aesthetic appeal of the part, (2) analysis of fluid flow through different orifice designs in valves fabricated by RP, (3) wind tunnel testing of different streamline shapes using a physical models created by RP, (4) stress analysis of a physical model, (5) fabrication of preproduction parts by RP as an aid in process planning and tool design, and (6) combining medical imaging technologies, such as Magnetic Resonance Imaging (MRI) with RP to create models for doctors in planning surgical procedures or fabricating prostheses or implants (Chua, Leong and Lim, 2010).

"This way, they can hold the actual heart in their hand, the physiology of that heart, the rendering of that heart, and pregame the direction of the tools, the angle of the tools and how they're going to attack different vessels."

Mark Ginsberg (cited by Jackson, 2013).

2.4.3 Tooling and Manufacturing

The trend in RP application is toward its greater use in fabrication of production tooling and in the actual manufacture of parts. When RP is adopted to fabricate production tooling, the term rapid tool making (RTM) is often used. RTM applications divide into two approaches (Chua, Leong and Lim, 2010). Firstly is the indirect RTM method, in which a pattern is created by RP and the pattern is used to fabricate the tool, and direct RTM method in which RP is used to make the tool itself (Hilton, 1995). Example of indirect RTM include use of an RP-fabricated part as the master in making a silicon rubber mold that is subsequently used as a production model (Kai and Fai, 1998). In the other hand, the example of direct RTM include RP-fabricated mould cavity inserts that can be sprayed with metal to produce injection moulds for a limited quantity of production plastic parts (Kai and Fai, 1998). Lastly, the example of actual part production include small batch sizes of plastic parts that could not be economically injection moulded because of the high cost of the mould (Pham and Gault, 1998).

2.4.4 Other Examples of RP Applications

The other example of RP applications is the production of the hearing aids. The hearing aid shape fit the shape of the patient internal ear by Selective Laser Sintering (SLS). Pigmented PA 12 (Nylon) is used as material since it fulfils all the pre-requisites including mechanical properties and skin compatibility (Levy et al., 2003).

Besides that, RP is also used in dental medicine for alignment of teeth using bridges. The individual teeth correction is calculated step by step with appropriate software. New modified impression is exported for each correction of about 12 stages as a solid design. By wearing the bridges in the mouth, teeth alignment is achieved stage by stage. It is customized by tooling manufacturing and indirect bridge production (Levy et al., 2003).

RP technology also had been used by the Boeing Co. Air ducting for the aerospace is manufactured by SLS within hours on a Vanguard SLS System. Complex components that are difficult to manufacture via traditional technologies are quickly manufactured on that system, at lower cost and in fewer segments (Levy et al., 2003).

Automobiles also similarly benefit from lighter parts, which as cited by Freedman (2011), “University of Louisville’s Gornet notes that printing process could cut the weight of valves, pistons and fuel injectors by at least half”. This leads to some manufacturer of ultra-luxury and high-performance cars, including Bentley and BMW, are already using 3D printing for parts with production runs in the hundreds (Freedman, 2011).

2. 5 BASIC PRINCIPLES OF SILICONE RUBBER

Silicone Rubber (SR) is a manmade product derived from natural products – silicone and rubber. It is made by curing or vulcanizing natural rubber. Silicone is injected into the long hydrocarbon chains of natural rubber under high heat and pressure. The result is SR. In a simpler way, SR is a silicone polymer with rubberized qualities (Pam, 2012).

SR compounds have characteristics of both inorganic and organic materials, and offer a number of advantages not found in other organic rubbers. SR have fine electrical properties, good chemical stability and flame retardancy and superior resistance to heat and cold. They are used in nearly every industry to improve the quality and functionality of products including electric and electronic equipment, office automation equipment, automobiles, food products, household goods and leisure products (Pam, 2012).

2.6 GENERAL PROPERTIES OF SILICONE RUBBER

SR have a lot of advantages. Firstly, SR have exceptional weatherability. Ozone created by corona discharge deteriorates most organic rubbers, but has almost no effect on SR. In addition, SR can be exposed to wind, rain and UV rays for long periods with virtually no change in its physical properties (Etsu, 2012).

Secondly is moisture and steam resistance. SR can be immersed in water (cold water, warm water, boiling water) for long periods with water absorption of about 1% and with virtually no effect on mechanical strength or electrical properties. Typically, under ordinary pressure, contact with steam causes almost no deterioration of SR. with pressurized steam, however, the effects increase as steam pressure increases. High pressure steam at temperature over 150 degree Celsius causes breakdown of the siloxane polymer and a decline in the properties of rubber. This effect can ameliorated by adjusting the silicone rubber formula, selecting a proper curing agent, and post curing. There are numerous products available with improved resistance to steam and hot water (Etsu, 2012).

SR also has high heat and cold resistance, far better than organic rubbers. SR can be used indefinitely at 150 degree Celsius with almost no change in properties. It withstands use even at 200 degree Celsius for 10, 000 hours or more. Besides that, SR also has excellent resistance to cold. The embrittlement point of typical organic rubbers is between -20 to -30 degree Celsius, compared to -60 to -70 degree Celsius for SR. even at temperatures at which rubbers turn brittle, SR remains elastic (Etsu, 2012).

Silicone rubber has outstanding resistance to oil at high temperatures. Among common organic rubbers, nitrile rubber and chloroprene rubber have somewhat higher oil resistance at temperatures below 100°C, but at higher temperatures silicone rubber is superior. Silicone rubber also has excellent resistance to solvents and other chemicals. It is essentially unaffected by polar organ ic compounds (aniline, alcohol, etc .) or dilute acids or bases, with the increase in volume due to swelling in the range of only 10%-15%. Silicone rubber does swell in non-polar organ ic compounds like benzene, toluene and gasoline; but unlike most organic rubbers, it does not decompose or dissolve, and will return to its former state when the solvent is removed (Etsu, 2012).

SR also has high dynamic stress, with flex fatigue resistance that is 8-20 times higher than conventional products. The tear strength of silicone rubber is generally around 9.8 kN/m. There are high-strength types available with tear strength between 29.4 kN/m and 49.0 kN/m, achieved through polymer modification and/or judicious select ion of fillers and crosslinkers (Etsu, 2012).

Other than that, most organic rubbers are black due to their carbon content. In contrast, it is possible to make highly transparent silicone rubber because the fine silica it contains does not spoil the natural transparency of silicone. Its high transparency makes silicone rubber easy to color with pigments, so manufacturers can produce colorful molded items. Thus it is suitable for artistic products (Etsu, 2012).

Finally, SR is chemically inert with good release properties, so it does not corrode other materials. Living tissues also are affected by contact with silicone rubber to a lesser degree than by exposure to other organic polymers. This means SR is also physiologically inert (Etsu, 2012).

CHAPTER 3: METHODOLOGY

3.1 PROJECT FLOW CHART

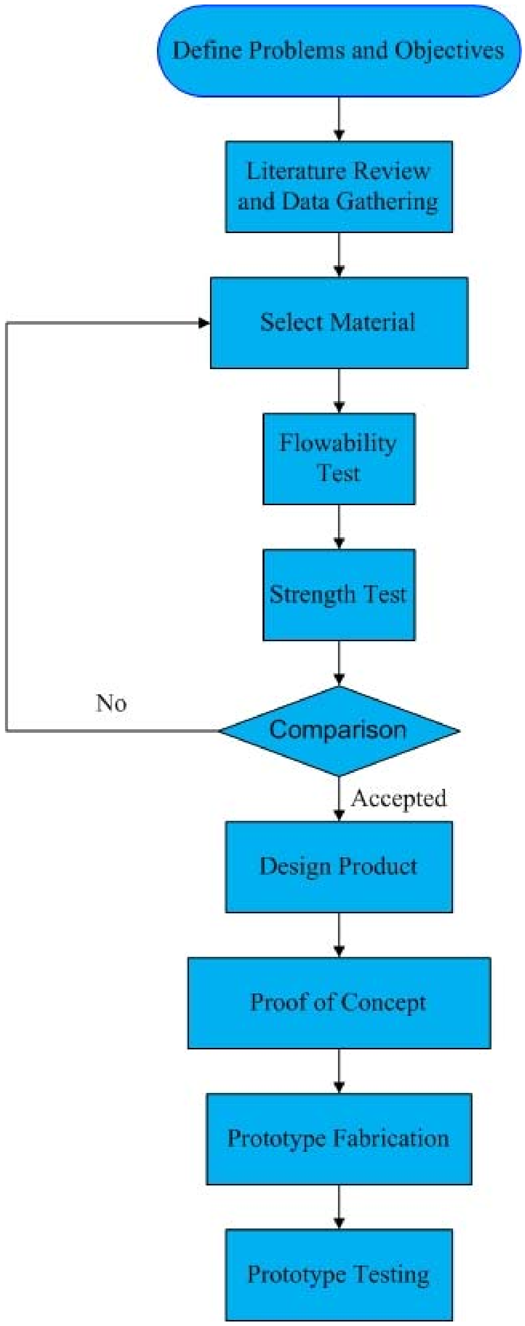


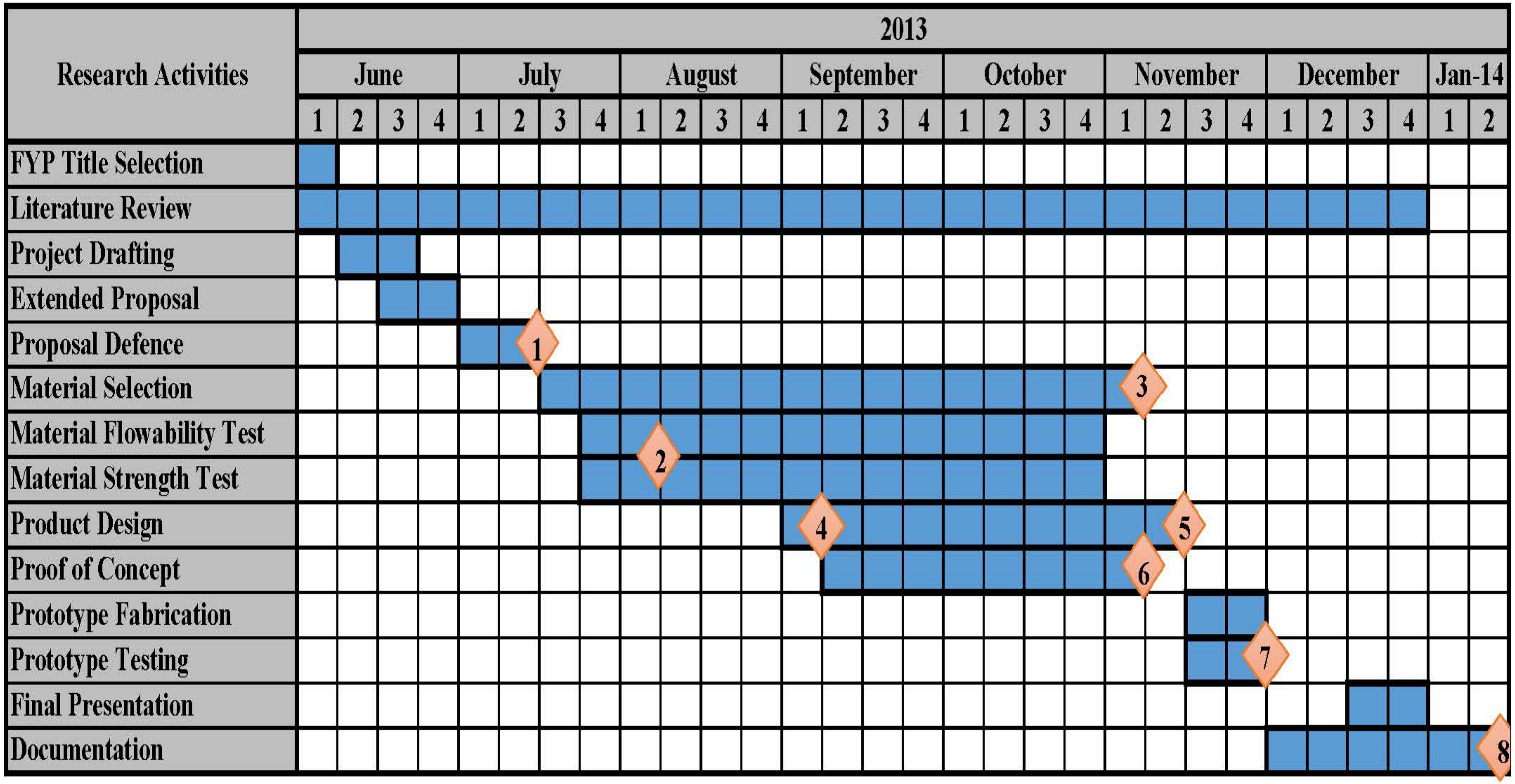
Figure 7. Project flow chart.

Based on the flow chart in Figure 7, the project was initiated by defining the problem and identifying the objectives. Once done, the author carried out an extensive study on the project by gathering required data from available journals, articles, books and references. This enabled the author to understand more on the project to be carried out and able to correlate the project with other previous researches done by researchers.

A few materials were chosen and tested. These includes Self-Compacting Concrete (SCC), Geo-Polymer Binder (GPB), Low Density Polyethylene (LDPE) and Silicone Rubber (SR). There might be some problems regarding the flow of material inside the scaffolding, however it is expected that it would be solved by increasing the cavity area of the scaffolding. With that, experimental setups are developed where the materials were tested by being poured into a 3D Printed scaffolding sample. This experiment was done to test the flowability of the material. After that, strength test was done simply by applying a small amount force on the sample. Final material was selected if the material pass both test. All the design process will be done in a 3D CAD modelling software. Next, proof of concept was done by making a simple model which replicates the function of the real prototype.

The design was then be fabricated with RP machine. The product from the RP machine will be the scaffolding to where material will flow into. The material was then left to solidify, and develops its strength, allowing it to form the shape of the scaffolding. Finally, the prototype is tested for its functionality.

3.2 PROJECT GANTT CHART AND KEY MILESTONES



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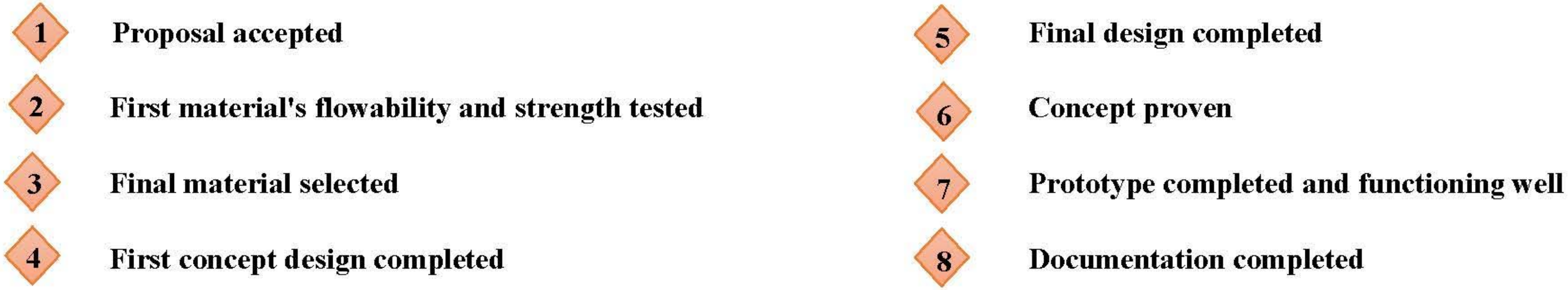
Material Strength Test								■	■	■	■	■	■	■	■	■	■	■	■	■										
Product Design													■ 4	■	■	■	■	■	■	■	■	■ 5								
Proof of Concept														■	■	■	■	■	■	■	■ 6									
Prototype Fabrication																							■	■						
Prototype Testing																							■	■ 7						
Final Presentation																											■	■		
Documentation																									■	■	■	■	■	■ 8

Figure 8. Gantt chart.



1. **Proposal accepted**
2. **First material's flowability and strength tested**
3. **Final material selected**
4. **First concept design completed**
5. **Final design completed**
6. **Concept proven**
7. **Prototype completed and functioning well**
8. **Documentation completed**

Figure 9. Key milestones.

3.3 GOVERNING EQUATIONS

Given the design specifications, the rotational speed of the ball, velocity of the impeller can be estimated from:

Equation 1

$$v_f = \frac{2\pi r\omega}{60} \text{ (m/s)}$$

ω = Rotational speed of impeller

r = Radius of impeller

v_f = Velocity of impeller

Next, with the velocity of the impeller, the speed of water at outlet can be estimated through the conservation of force in inelastic collision:

Equation 2

$$m_w v_{wi} + m_b v_{bi} = (m_w + m_{wb}) v_f$$

$$v_{wi} = \frac{(m_w + m_b) v_f - m_b v_{bi}}{m_w} \text{ (m/s)}$$

m_w = Mass of water

m_b = Mass of impeller and ball

v_{wi} = Initial velocity of water

v_{bi} = Initial velocity of impeller and ball

v_f = Final velocity of water, impeller and ball

However, it is estimated that kinetic energy will be reduced through the water channel. Assuming efficiency is 90%, the inlet velocity is estimated.

Equation 3

$$KE = (0.9)\frac{1}{2}Mv_i^2 = \frac{1}{2}Mv_o^2$$

$$0.9v_i^2 = v_o^2$$

$$v_i = \sqrt{\frac{v_o^2}{0.9}} \ (m/s)$$

KE = Kinetic energy

v_i = Velocity at inlet

v_o = Velocity at outlet

With velocity of water at inlet, volume flow rate of the water can be estimated by:

Equation 4

$$Q = Av_{wi}\ (m^3/s) \quad \text{where} \quad A = \pi r_{wc}^2$$

Q = Volume flow rate of water

A = Cross sectional area of water channel

r_{wc} = Radius of water channel

Pressure of water source can be estimated from the volume flow rate by:

Equation 5

$$P = \frac{\rho Q^2}{2A^2}\ \text{(Pa)}$$

P = Pressure of water source

ρ = Density of water

Thus, with the pressure of water source estimated, a water pump with the nearest pressure rating should be used.

Force given from the water, can be calculated by:

Equation 6

$$F = PA\ \ \text{(N)}$$

F = Force

A = Cross sectional area of water channel

Q = Volume flow rate of water

Finally, assuming force is conserved from inlet to outlet, torque developed by the impeller is estimated from:

Equation 7

$$T = Fr\ \ \text{(Nm)}$$

A = Cross Sectional Area of water channel

T = Torque

r = Radius of impeller

CHAPTER 4: RESULT AND DISCUSSIONS

4.1 MATERIAL SELECTION

A few materials had been tested which were the Self-Compacting Concrete (SCC), Geo-Polymer Binder (GPB), Low Density Polyethylene (LDPE) and Silicone Rubber (SR).

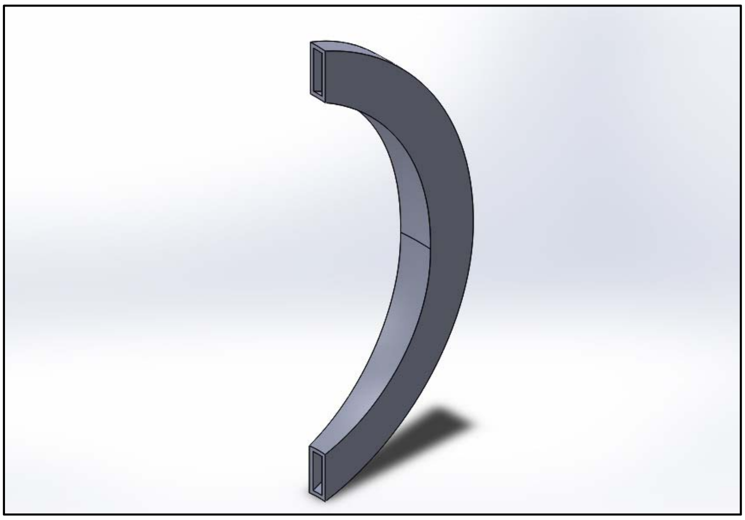


Figure 10. The scaffolding sample design. (Cavity = 16mm x 4mm)

Figure 10 above shows the scaffolding sample design from 3D Printer The following table shows the result of the material test:

Table 1. Material test result

Material	Flowability Test	Strength Test
SCC	Failed	-
GPB	Passed	Failed
SR	Failed	-
SR	Passed	Passed

Based on Table 1, the first material, SCC was not able to flow through the cavity & fill the sample. Thus, it failed the flowability test. The reason was because the course aggregate inside the SCC was too big in diameter, causing it not being able to pass through the cavity. Strength test was not conducted for this material since it did not pass the flowability test.

Next tested material was the GPB. The GPB was able to flow through the cavity and fill the sample without any problem. However, it broke and failed from just a small amount of force & failed the strength test.

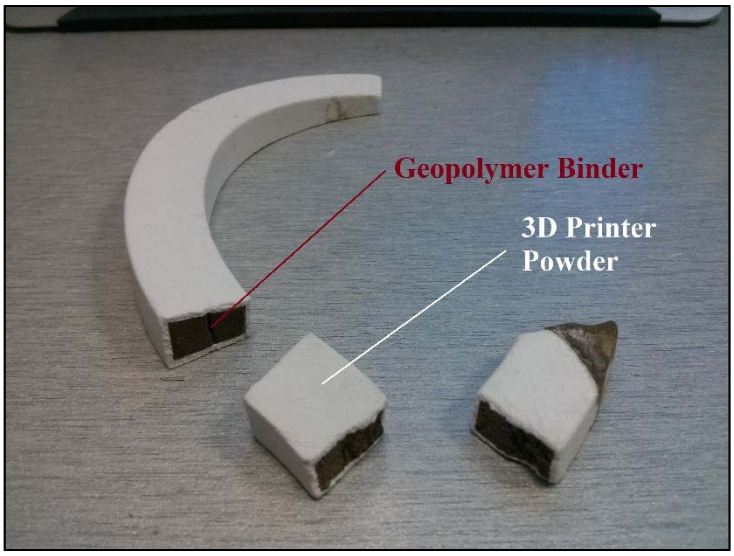


Figure 11. A broken scaffolding sample filled with GPB.

Figure 11 shows the sample filled with GPB which have been broken by a small amount of force. The one in white is the powder from 3D Printer and the brown coloured is the GPB. SR also did not passed the flowability test, same as the SCC. However, the reason was because the LDPE cured too quickly. It hardens before it can fully filled the sample. Thus it was not able to fill the sample completely.

Finally, SR was tested. It was able to fully fill the sample without any problem and passed the flowability test. For the strength test, although it does not has high strength, it was made up by its high elasticity and toughness. Because of this property, the sample deformed, however it did not break and did not fail, because it would return to its original shape once force was no longer applied.

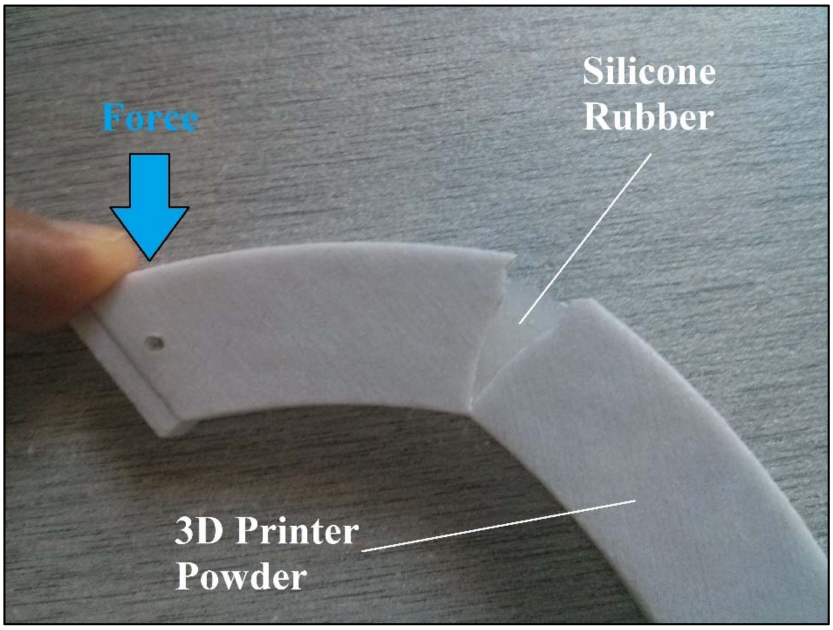


Figure 12. A deformed silicone rubber.

Figure 12 above shows that when force is applied, the silicone rubber inside the scaffolding deformed and the scaffolding made of 3D printer powder breaks. However, when the force is released, the SR will turn back into its original shape due to it being ductile. Since it did not break or failed, SR passed the strength test. Thus with SR passing both the flowability and strength test, it was chosen as material for the prototype.

4.2 PROTOTYPE DESIGN

Several conceptual design had been developed for the product. All the designs are formed under one concept, which was moving an object with fluid. The fluid to be used in this project would be water.

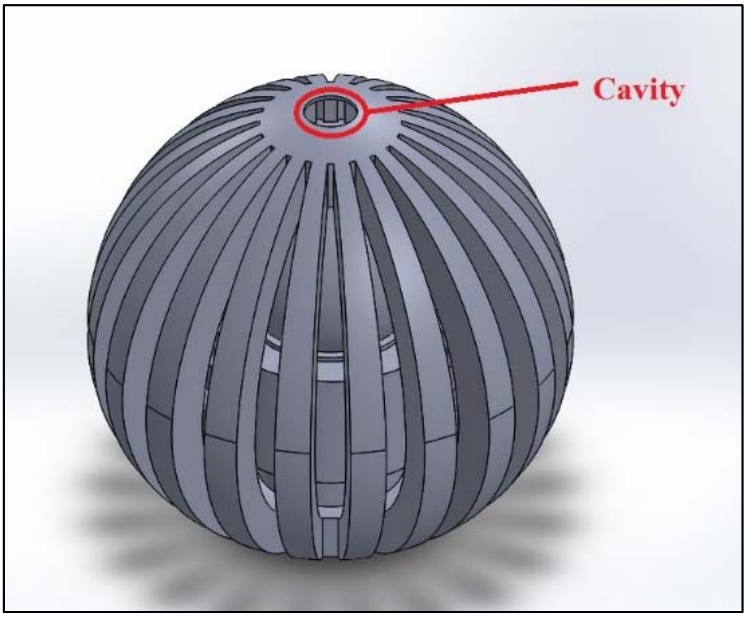


Figure 13. General design. (Isometric View)

Figure 13 shows the general design of all the conceptual design. This means all the conceptual design will be designed almost identical with the one shown above. Material will flow inside the scaffolding through the cavity on top of it. The concept is to have a rotating part inside the cage by channelling water or a water featured cage.

4.2.1 Rev 0

Figure 14 below shows the first conceptual design (Rev 0).

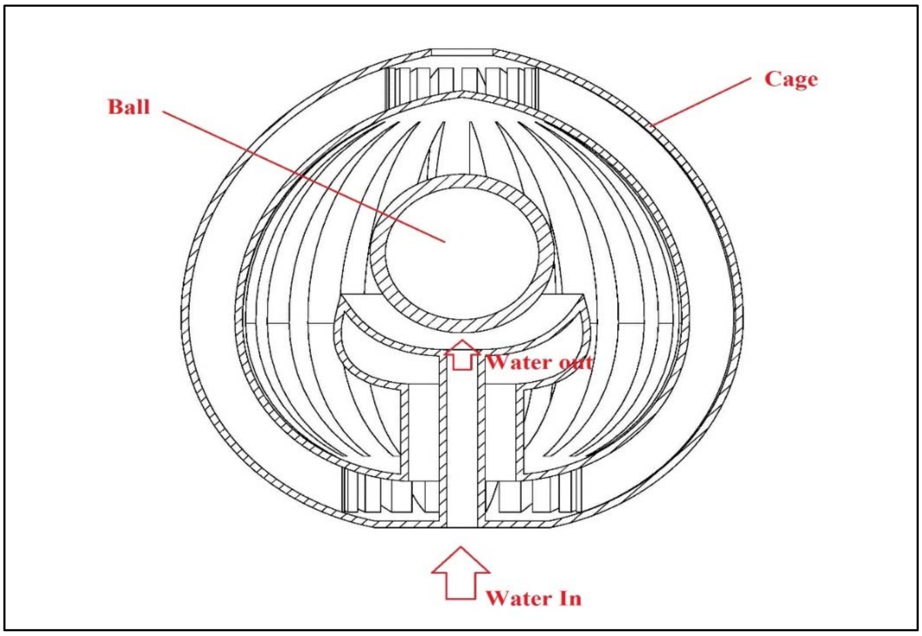


Figure 14. Rev 0. (Front section view)

Rev 0, functions by having the water coming from the bottom of the ball causing the ball to rotate in the direction as shown in Figure 15 below.

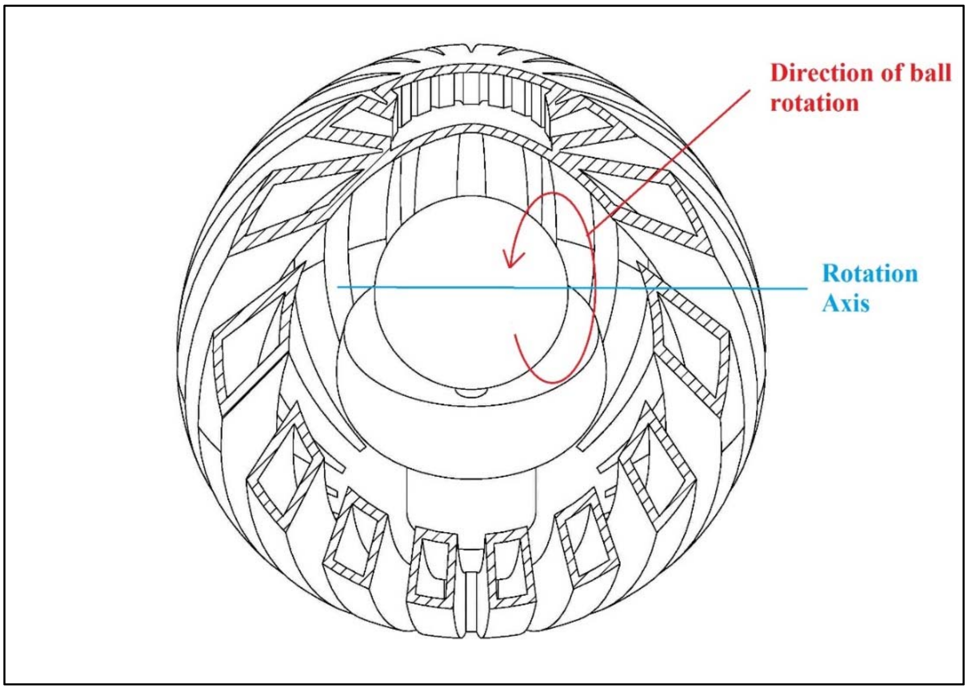


Figure 15. Rev 0 ball rotation.

4.2.2 Rev 1

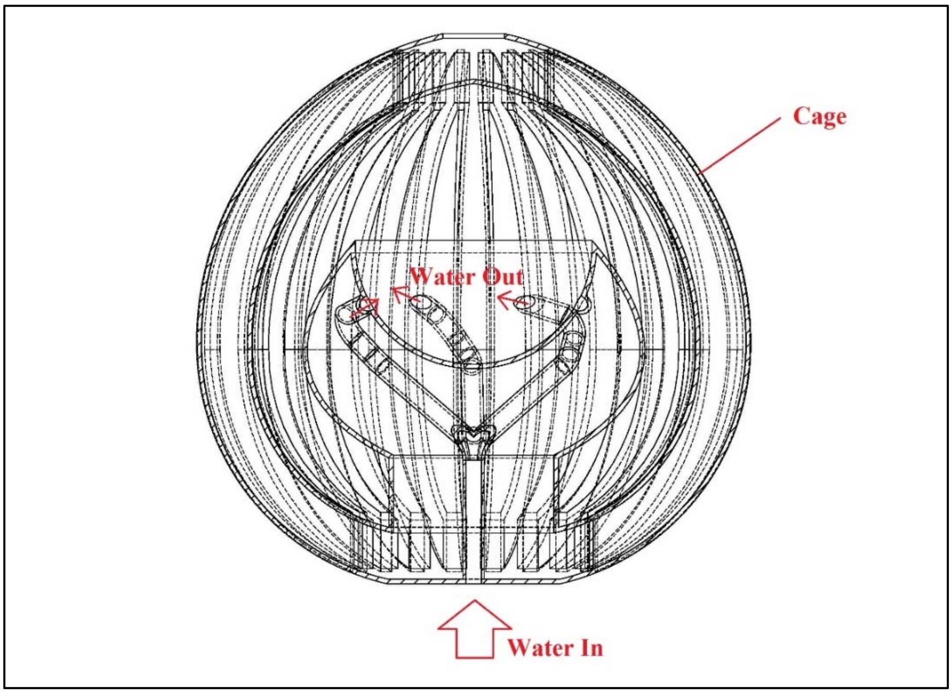


Figure 16. Rev 1. (Front view)

Based on Figure 16, the ball is intentionally hidden to show a clearer view of the water pathway in Rev 1. The author decided to make the ball rotate in another way to make it more attractive to anyone seeing it, since the prototype would be mainly for decoration purposes. The water channel leads the water to come out from the sides of the ball. This will cause the ball to rotate in the direction as shown in Figure 17, anti-clockwise when viewed from the top.

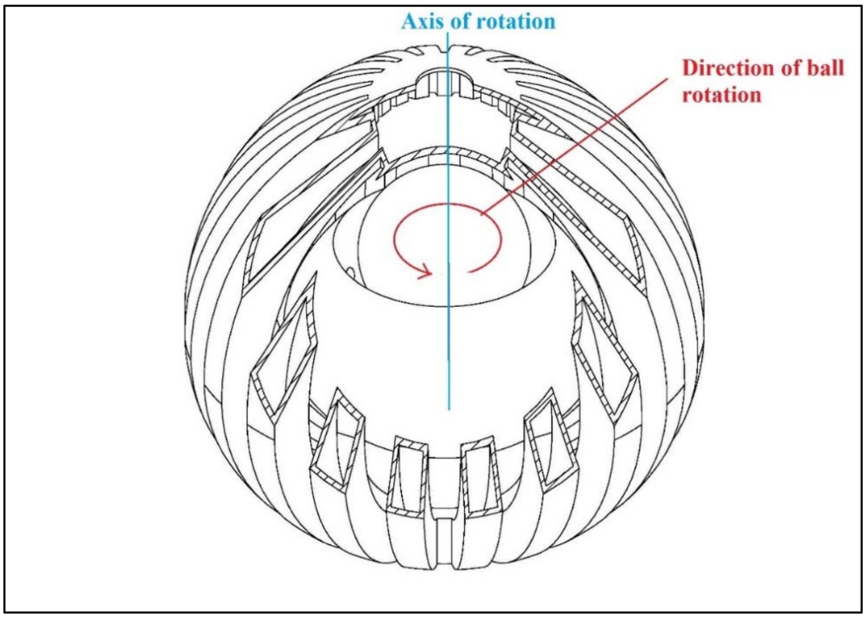


Figure 17. Rev 1 ball rotation.

4.2.3 Rev 2

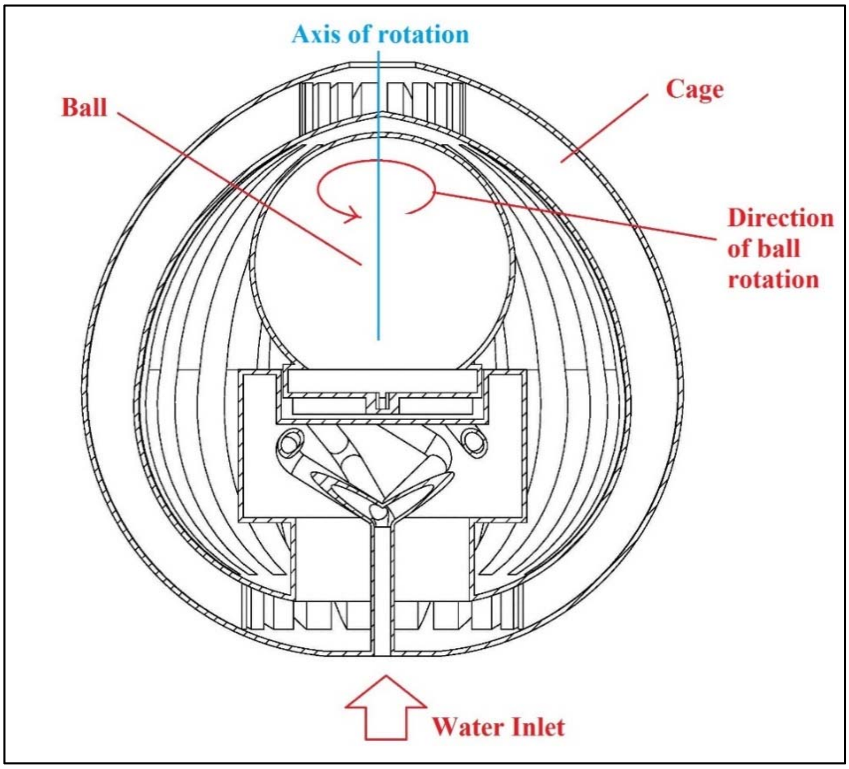


Figure 18. Rev 2 (Front section view).

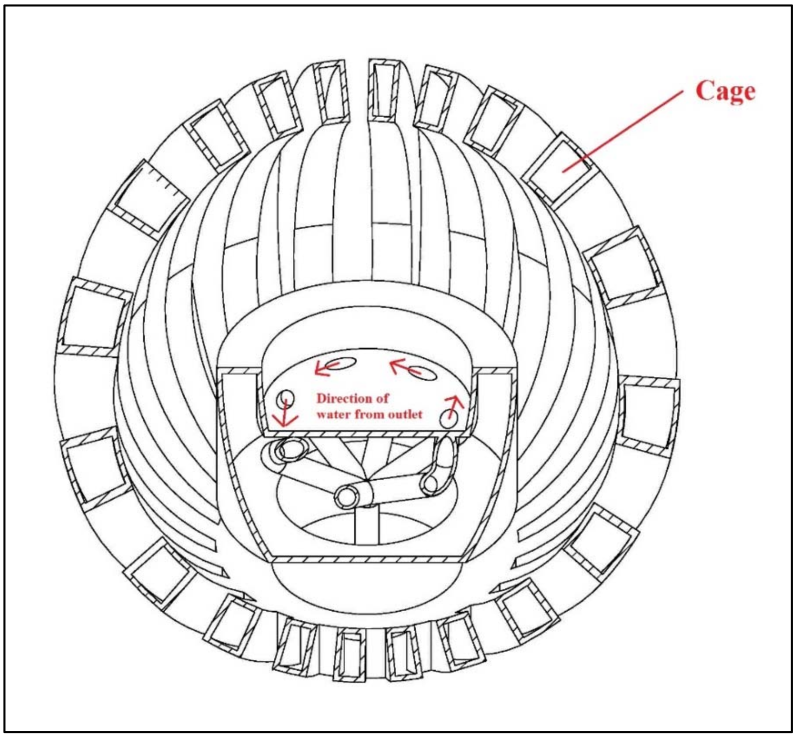


Figure 19. Rev 2 (Isometric section view).

As shown on Figure 18, the ball will spin in the same direction as in Rev 1, anti-clockwise when viewed from the top. Next, as shown in Figure 19, the water channel leads the water to come out from bottom of the ball while shooting sideways. To allow this, the ball was designed like an impeller and mimics the dynamics of impeller as well. Shown in Figure 20 is the ball design of Rev 2.

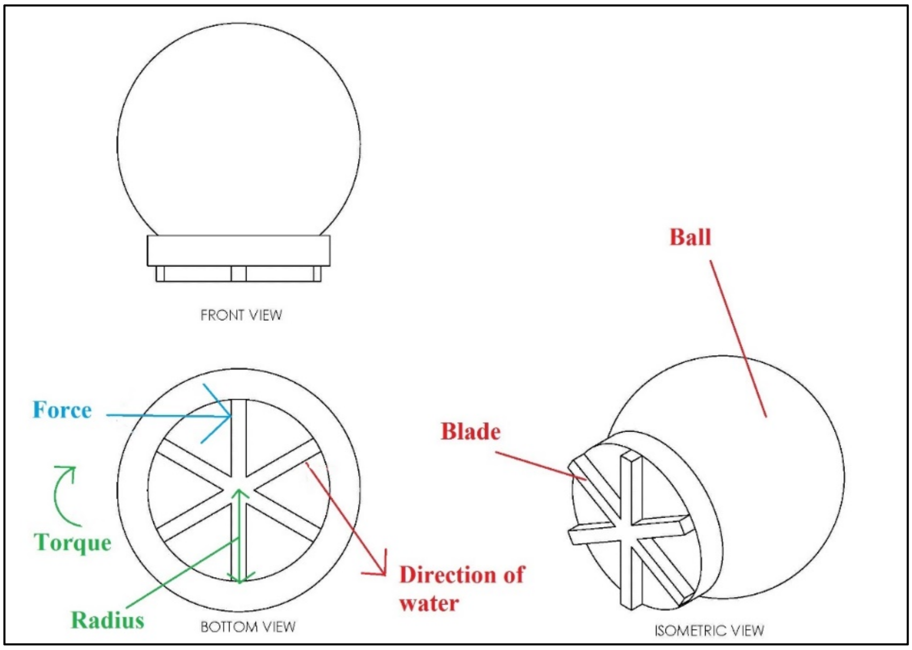


Figure 20. Rev 2 ball and impeller design.

Based on Figure 20, water will be directed to the blade. The pressure from the water will develop a force on the blade and that force will develop a torque in the direction as shown in the figure.

4.2.4 Final Design

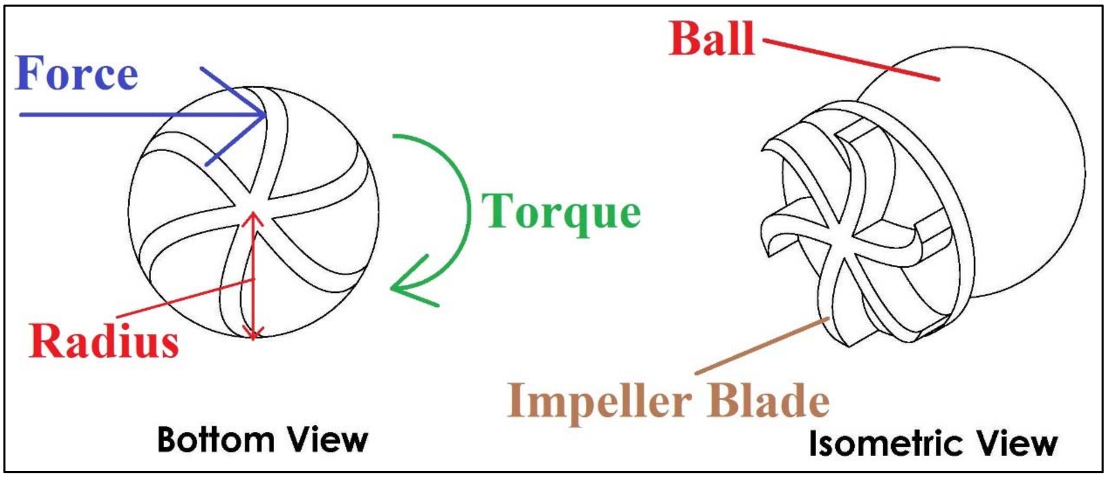


Figure 21. Rev 3 Ball and impeller design.

Based on Figure 21, the impeller blade has been made curved for Rev 3. This was to make it more practical, as a curved blade will produce less noise than a straight blade. However, less noise come at the expense of a significant loss in performance caused by the fact that curved blades stall at a lower static pressure than straight blades. If an impeller moves less fluid, then, simply you can expect less noise. However, for this project, the performance or rotating speed of the ball and impeller was not a major concern as long as it can rotate. Rev 3 was the final design of the prototype and shown in Figure 22 is the front section view of the final design.

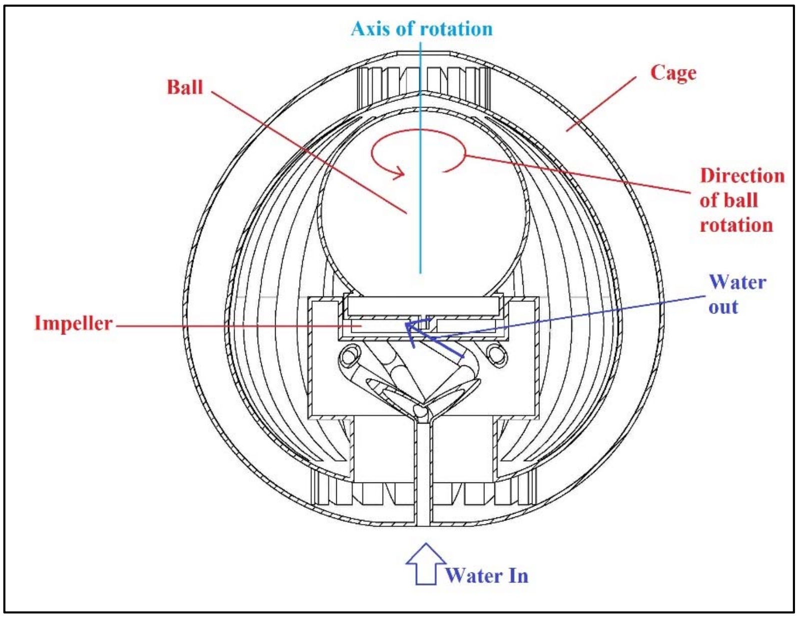


Figure 22. Final design (Front section view).

Based on Figure 22, it can be seen that the dynamics is same with Rev 2, where the ball will rotate anti-clockwise when viewed from the top. Water will be channelled in from bottom of the design, and out to the side of the impeller blade. Pressure from water will provide a force on the blade. From the force, torque is developed and the impeller rotates, rotating the ball on top of it as well.

4.3 PROOF OF CONCEPT

Proof of Concept (PoC) was done in order to ensure the prototype will function as desired. For this case, a simple model which mimics the functionality of the real prototype was made. The model was then tested with a water source to see whether the impeller would rotate or not. Below are the result from the PoC.

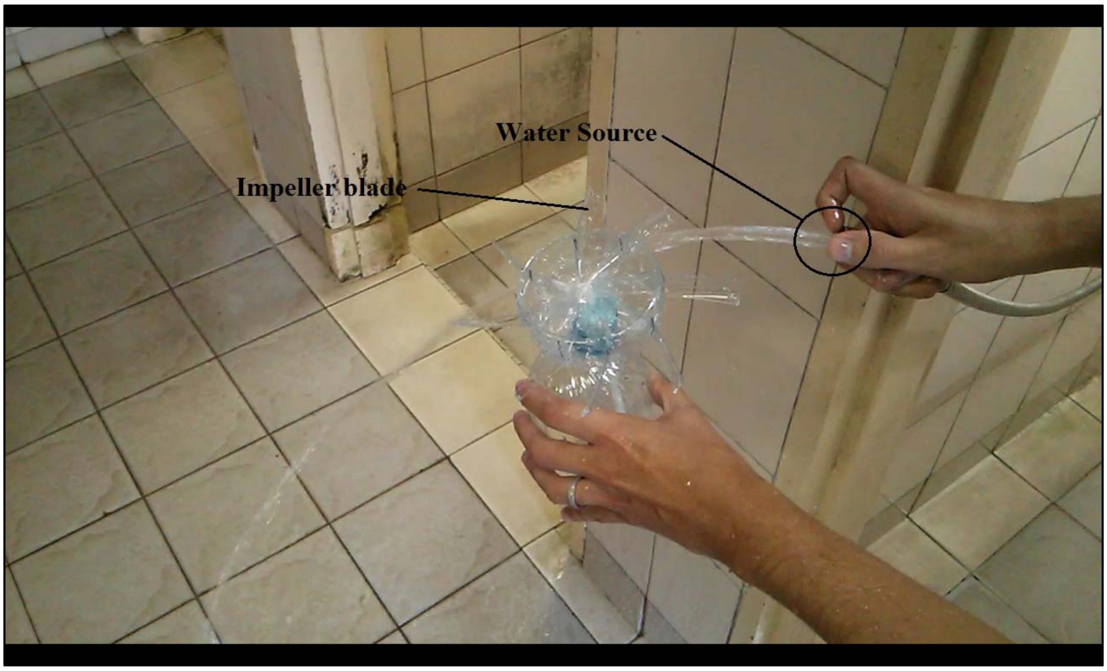


Figure 23. The PoC model before water hits the blade.

Shown in Figure 23 is the model before water hits the blade. Thus it was static.

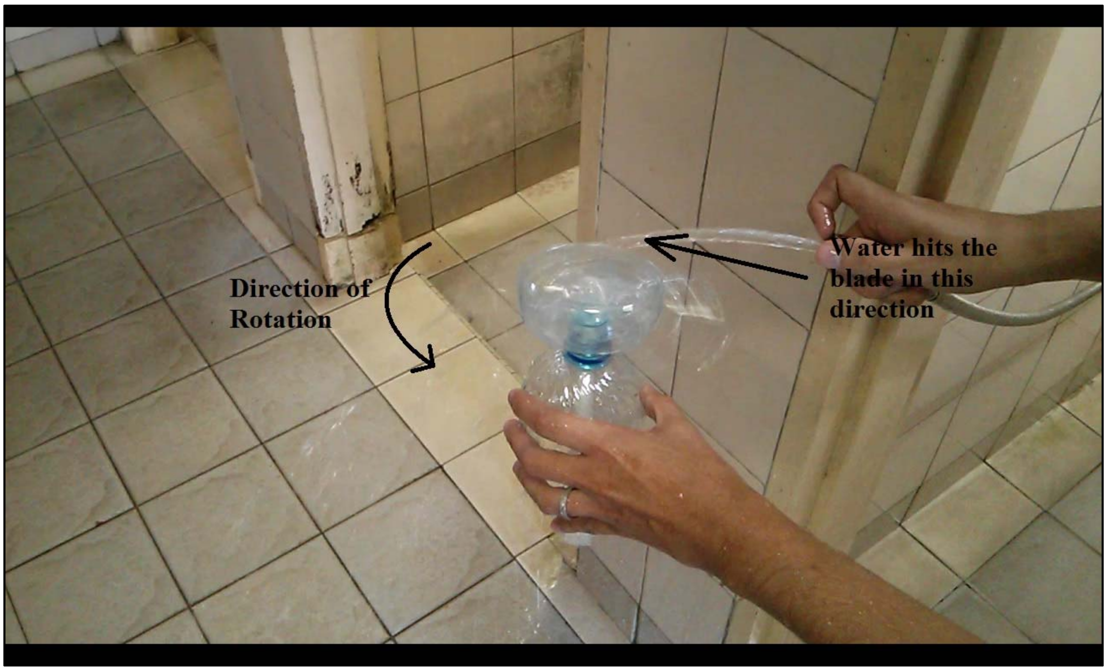


Figure 24. PoC model after water hits the blade.

Shown in Figure 24 is the result of water hitting the blade of the model. The model was rotating in an anticlockwise direction when viewed from the top. Since there was no problem in rotating the model, the author had assumed that the final prototype design will be functioning as desired.

4.4 CALCULATIONS

Given the design specifications, to rotate the ball at 60 rotation per minute and the radius of the impeller is 30mm, the rotational speed of the impeller is:

$$v_f = \frac{2\pi r\omega}{60} = \frac{2\pi(0.03)(60)}{60} = 0.19 \ m/s$$

Assuming 5g of water hit the impeller at a time. The speed of water at outlet is:

$$v_{wi} = \frac{(m_w + m_b)v_f - m_b v_{bi}}{m_w} = \frac{(0.005 + 0.08)(0.19) - (0.8)(0)}{0.005}$$

$$= 3.23 \text{ m/s}$$

Assuming efficiency is 90%, the inlet velocity is:

$$v_{wi} = \sqrt{\frac{v_o^2}{0.9}} = \sqrt{\frac{3.23^2}{0.9}} = 3.4 \, m/s$$

Given the radius of water channel is 3.5mm, the volume flow rate of water is:

$$A = \pi r_{wc}^2 = \pi(0.0035)^2 = (0.0385 \times 10^{-3})m^2$$

$$Q = Av_{wi} = (0.0385 \times 10^{-3})(3.4) = (0.131 \times 10^{-3}) \, m^3/s$$

Density of water is 1000 kg/m^3. Finally the pressure from the water pump to be used should be:

$$P = \frac{\rho Q^2}{2A^2} = \frac{(1000)(0.131 \times 10^{-3})^2}{2(0.0385 \times 10^{-3})^2} = 5788 \text{ Pa}$$

Thus, the pressure rating of water pump used must be as close with 5788 Pa.

The force given by the water would be around:

$$F = PA = (5788)(0.0385 \times 10^{-3}) = 0.223\ N$$

Finally, assuming the force is conserved, the torque developed at is:

$$T = Fr = (0.223)(0.03) = (6.6 \times 10^{-3})\ \text{Nm}$$

4.5 PROTOTYPE FABRICATION AND TESTING

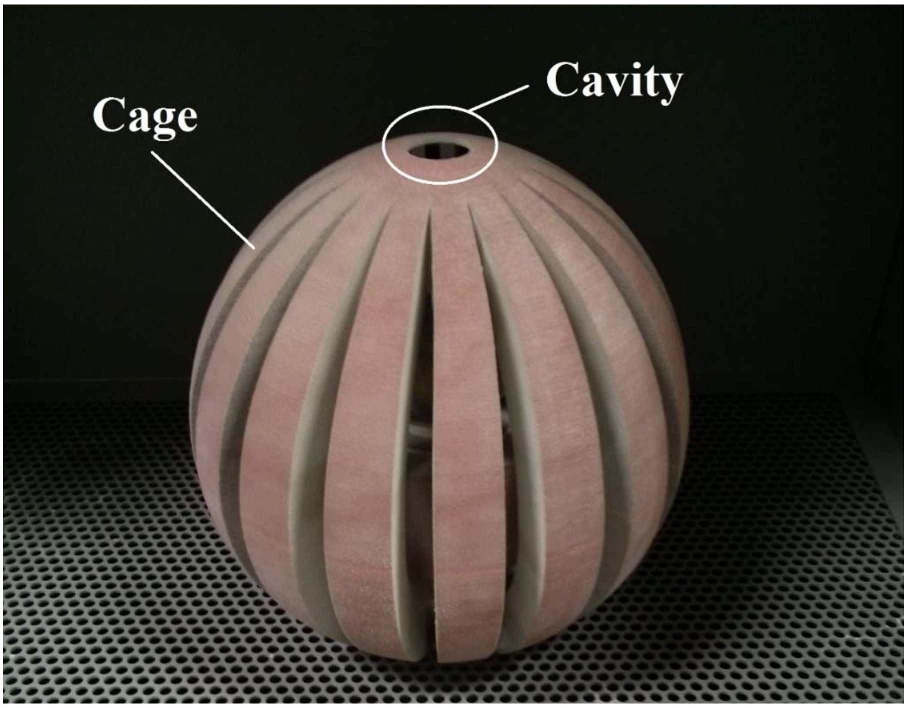


Figure 25. Prototype of the Water Feature Cage.

Shown in Figure 25 above is the prototype of the water feature cage after it was manufactured by the 3D Printer. The cavity on top of it is where the SR is poured in from and from there it started to fill the scaffolding throughout.

After that, the prototype was tested by connecting it to a water source. Unfortunately, the ball inside only turned for a while before it went out of balance and stopped rotating. The reason for this was because when the water travelled in the water channel from one inlet to six outlets, the volume of water was not divided equally among the outlets. This caused the water pressure and force developed at the outlets different between each individual outlets. When one outlet was giving a higher pressure and force than the others, the ball was lifted at the higher pressure region causing it to go out of balance.

Besides that, the fault was also partially because of error in the design. Having the outlet at the bottom of the impeller caused the impeller to be lifted up while it was rotating. If the water channel had been designed, having the outlets from the side of the impeller, the impeller would have not been lifted even if the pressure at the outlets were not balanced.

Finally, the problem was also because the project lacked in terms of computer simulation. Proof of concept alone was not enough to ensure the prototype is going to function as desired. The reason for this was because the model was not 100% identical to the prototype. For example, the model was lighter than the real prototype.

However, the functionality of the prototype was not a part of the project objectives. The project was already a success right after the prototype was manufactured and SR succeed to fill the whole scaffolding. The author had simultaneously overcame the limitations in both DFM and RP. Future work and more researches and time are needed in order to improve this project and to further perfecting it.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

It can be concluded that this project had fulfil all the objectives. This project investigated the improvement in overcoming the limitations in DFM of non-metallic objective embedded within a part through design and 3D prototyping with SR. From this project also, some limitation in RP were overcame. A physical prototype from the combination of RP technology and SR was manufactured. Lastly, the end product had created a new branch in Mechanical Engineering towards arts and aesthetic, which perhaps will create a new revolution for mankind.

However, there were problems with the functionality of the prototype where the ball and impeller stopped rotating. This can be improved by improving the design. One thing that can be improved is by adding an element to the design which will keep the ball and impeller balanced despite the different pressure between outlets given by the water.

Besides that, the design also can be improved by having the outlet from the side of the impeller. This way it would have not been lifted even if the pressure at the outlets are not balanced.

Thirdly, Computational Fluid Dynamics (CFD) can be used to simulate the rotation of the ball and impeller. This way, we can ensure that the prototype will be functioning as desired before the prototype is fabricated.

There are also some other recommendations to improve this project even further in the future. Firstly, is to replace the material. Instead of SR, the future project can use some other better materials. For example is by using melted metal which has better overall properties than SR.

Secondly, is to implement this project in the industries. The industries can be oil and gas, automotive, manufacturing, jewelleries, etc. One example that can be applied in oil and gas industry is the fire-and-forget equipment for deep water applications.

With these two recommendations, it is expected that this project will continue to contribute to the mankind by simultaneously overcome the limitations in both DFM and RP.

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