Additive Manufacturing &

Reverse Engineering

Quadcopter Re-design

Abstract
A reverse engineering project In which the Syma X5C drone is disassembled and remodelled using reverse engineering techniques. The final product was re-designed using the data that was acquired from scanning and the overall functionality was increased by integrating a speaker and also improving the aerodynamics of the drone shell.

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Statement of Contributions

Section	Contributors
Introduction	KF
Literature Review Additive Manufacture	KF
Literature Review Reverse Engineering	HT
Audio Review	HT
Disassembly & Analysis	HT, KF
Generating CAD File from DATA	DP
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1 Introduction

1.1 Overview

Additive manufacturing is increasingly being seen as the manufacturing method of choice for low volume bespoke products alongside its already huge market of prototyping. Manufacturing consists of growing a model by putting thin layers of material on top of each other in order to build the 3D part. The most common file type to produce these parts is .STL, which is a tessellated representation of geometry created in CAD software (1). The manufacturing process requires no bespoke tooling for each product and as technology develops, can match or exceed the strengths of those through traditional manufacturing processes such as casting and injection moulding. Additive manufacture also has it benefits over traditional processes as it gives the ability to create complex shapes and lightweight internal structures that cannot be produced any other way.

Reverse engineering can be defined as taking apart an object or product to see how it works in order to duplicate or improve the product (2). Additive manufacturing for reverse engineering is being increasingly utilised by household users. With the rise and development in household 3D printers, consumers are able to print essentially whatever they want at home. This could be used for tasks as simple as printing replacement parts of a broken product, right through to designing a new casings for electronic products, as seen in this project.

The market for drones is in massive growth presently. Drones in defence applications, known as UAV (Unmanned Aerial Vehicles), are becoming increasingly popular especially in war in zones where it is too risky to have soldier-manned vehicles (3). The military sector of the market is around 85% of the $8billion aerial drone market and is expect to increase to $12 million by 2024 (4). The civilian aerial drone market is also growing at the same speed with drones being used in business to make deliveries as well as used for pleasure (5). However, in recent months they have been receiving bad publicity due to instances of negligence leading to commercial drones being flown through restricted areas and striking passenger aircrafts (6).

For this report, a Syma X5C quadcopter drone is being reverse engineered and enhanced by adding a Bluetooth speaker (to play music and flying audio effects), along with changing its body to suit a more streamlined design, supplemented by Computational Fluid Dynamics analysis.

1.2 Aims & Objectives

The aim of this report is to reverse engineering and redesign a Syma X5C quadcopter drone to include a Bluetooth speaker system.

This will be completed using the following objectives-

1. Disassembling the product to analyse how it works and see the components inside.
2. Complete testing on the drone’s power output and determines a maximum weight limit for the new product.
3. Using laser scanners and metrology tools in order to create useable 3D CAD data of the complex parts.
4. Use NX to model an improved design of the drone.
5. Use a suitable additive manufacturing in order to manufacture the new quadcopter.
6. Assembly and test the new drone.

1.3 Work plan

The plan of work to be completed can be seen below

1. Literature review of reverse engineering. Including the process of RE for geometric object, different scanning methods and relating these to Cad model along with industrial trend and technology development.
2. Literature review of additive manufacture. Heavily confused on material extrusion and SLS along with industrial trend and technology development.
3. Review of drone market and design.
4. Review of the process of getting the CAD file from the RE techniques.
5. Manufacturing report for parts.
6. Discussion of resulting parts and further development required.
7. Conclusion of results.

2 Literature Review on Additive Manufacturing

2.1 What is additive manufacture?

The American Society for Testing and Materials (ASTM) international standard for additive manufacture (AM) lays out a set of definitions and terminology associated with the family of AM processes. It describes AM as the act of creating objects from 3D model data, usually layer upon layer (7). AM is very different to traditional subtractive manufacturing processes such as milling or turning and in turn, has different applications.

The ASTM standard F42 separates the family of AM processes into 7 categories which are:

- Binder Jetting
- Material Jetting
- Sheet Lamination
- Direct Energy Deposition
- Power Bed Fusion
- Vat Photo-polymerisation
- Material Extrusion.

The latter three of these are available to the group in this project are explained further in this review.

AM is commonly used to manufacture low volume prototype parts with short turnaround times and is also used for low volume production. Parts are manufactured in this way usually due to cycle time constraints being shorter than conventional methods but with a constant price against volume produced. High volume are not always economically wise, however the tooling cost is usually low meaning low volume production is a viable option. AM can be used for; form, fit and functional testing where physical models are required to demonstrate a design, or be used in testing (8). This is frequently seen in the automotive industry where project time constraints reduce the amount of time a product can be in development. For most industries, there can be up to 6 weeks lead time for prototype tooling which may not be a viable option (9). This is a perfect situation where AM methods can be used.

2.2 The process of Additive Manufacture

The process of taking a part from a Computer Aided Design (CAD) model to a physical model using AM includes 5 key steps (10), which are similar for each of the process categories. These are:

1. Generation of a CAD model using suitable CAD software, such as NX or solidworks.
2. Converting the CAD model to a .stl file. A .stl file is the standard data transmission format used for additive manufacturing processes (8). This format generates a tessellated representation of the CAD model surfaces. A higher cell density results in a more refined surface but leads to increased processing requirement.
3. Setting up the build. Once the AM process has been selected, the part orientation must be set up in the controlling software with the addition of support structures (for Material Extrusion and Vat Photo-polymerisation). Other process parameters such as the layer thickness and fill density can be set.
4. The component is now ready to be manufactured. The part can be manufactured autonomously and can be interrupted if required (to insert circuitry or parts).
5. Post processing. The amount of post processing for parts differs greatly between the process categories. For example material extrusion will require support structure to be removed; binder jetting requires additional infiltration; powder bed fusion required excess powder to be removed; and vat photo-polymerisation requires UV curing.

2.3 Advantages of Additive manufacture

There are many benefits of AM which is why it has become so popular. One of the main advantages is the speed it can produce components from scratch, due to the lack of tooling and fixtures required before a component can be manufactured. Prototyping is a common example, as parts can be created rapidly, hence the origin of the name ‘rapid prototyping’ (8).

AM can be used to reduce the number of processes needed to manufacture a part in comparison to conventional subtractive processes, where multiple processes and tool changes may be required. In AM the whole part is grown as a single part removing the need for any additional processing methods. (8) It also removes the need for skill craftsman when producing one off prototypes.

AM can make parts and components that wouldn't have been able to be produced conventionally, due to complex geometry, internal structures or hollow patterns, significantly reducing the weight of a part. This is used in the Formula One industry to make parts which could have been impractical to make without the use of AM methods (11). Internal structures within an AM part can be seen in Figure 2-1.

Figure 2-1 Internal structures within an additive manufactured part

2.4 Disadvantage of Additive Manufacture

Although the process is quick with regards to overall lead time, the cycle time per component is much higher than processes such as injection moulding or casting. Therefore after the production of a certain number of components, the cost and time of using a conventional process works out more economically viable than AM. (12) Figure 2-2 shows a graph that visualises this breakeven point for the cost per unit and number of components manufactured.

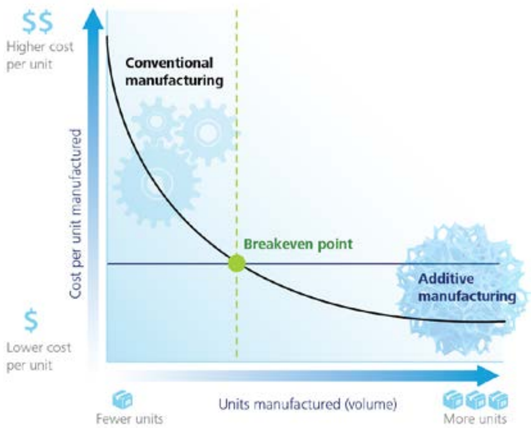

Figure 2-2 - Breakeven analysis comparing conventional and additive manufacturing processes (12)

Accuracy in the components produce via AM is very problematic; one of the biggest issues seen is the stair-stepping effect. This is due to the nature of parts being built layer by layer, and the approximations required making curves. Figure 2-3 shows how the desired shape compares to the actual shape produced from AM.

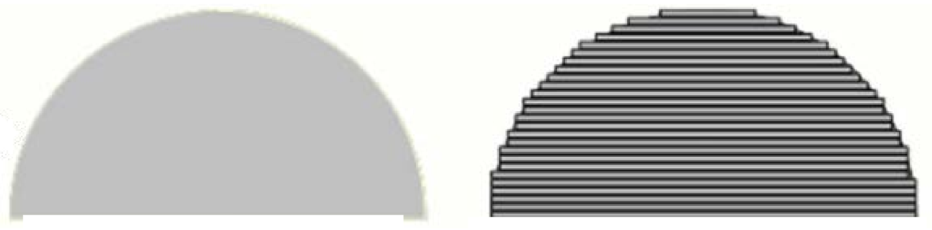

Figure 2-3- the effects of the stair stepping effects

This effect can be reduced by decreasing the layer thickness; however this can cause a huge increase to the time to complete the process. Therefore to try and reduce the stair stepping effect but still keep the processing time at a reasonable level, adaptive slicing can been used as seen in Figure 2-4. This allows the layer thickness to be varied throughout a print, and when necessary the layer thickness can be reduced to minimalise the stepping effect. This can be done where there is a lot of curvature in the Z axis. (13)

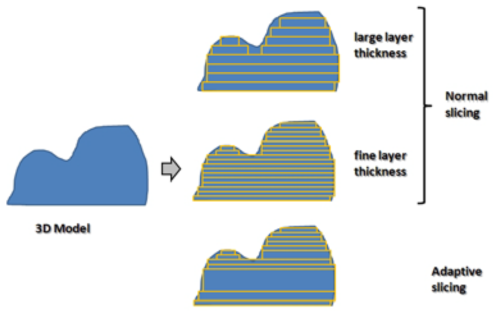

Figure 2-4 - the Stair-Stepping Effect in AM (14)

However despite all the attempts to reduce this effect, it cannot be complexly eliminated.

2.5 ASTM categories available to the group

There are 3 process families available to the group; each is explained below with an example of when it is applicable to be used along with a comparison between each process.

2.5.1 VAT Polymerisation

Also known as photo-stereo lithography or SLA for short, this process was initially developed and commercialised by 3D Systems in 1986. This process involves spatially controlled solidification of a liquid resin by photo-polymerisation; this is completed using a laser (top up method –Figure 2-5) or digital light projector (bottom up method- Figure 2-6). The process involves a pattern being cured to a certain depth, then in the top up method the build platform will drop, the top is recoated with liquid resin and levelled with a sweeper, and the next layer can then be cured. In a bottom up approach the part is built below a platform, the platform moves up after each layer has been cured, allowing the resin to run underneath it. As a result, this method does not require a sweeper. (15)

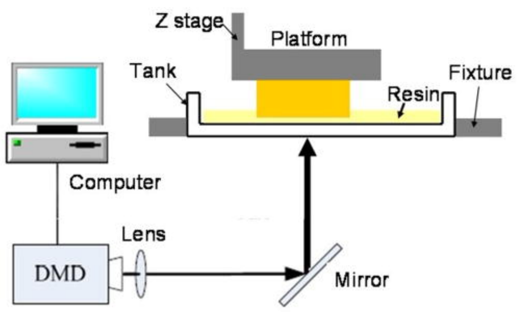

Figure 2-6- Bottom up approach to SLA (27)

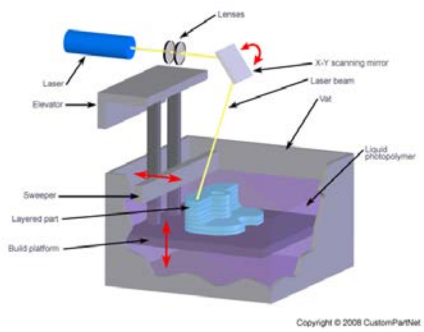

Figure 2-5 - Top down approach to SLA (28)

The machine available to the group is a bottom up 3D system viper system that is capable of layer sizes of 50 microns and resolution of position of 2.5 microns (16). This allows for a highly accurate surface and this is one of the benefits of this process. The quality of parts is also far superior to other AM processes (17). SLA parts are prone to being degraded by light due the parts being created from a UV resin, which can continue to cure leading to a colour change being seen. (REF) Due to SLA being one of the quickest AM process, it is often used for prototyping. Parts which will ultimately be injection moulded usually have prototypes made with SLA. This is because the material properties and shape accuracy are of a similar level of injection moulding, allowing for good fit and function testing. (17) SLA parts are also used in the medical world, for parts used as hearing aids and implantable devices such as tissue scaffolds, which biodegrade in the body. (15)

2.5.2 Powder Bed Fusion

Powder bed fusion is also known as selective laser sintering (SLS) or selective laser melting, depending on the materials involved. This process involves using a laser to solidify successive layers of powdered material. The solidification can be obtained through fusing, sintering or melting the powder. Once a layer has been solidified the platform will drop lower into the power bed, and a levelling roller will coat additional powder onto the top allowing for the process to continue on a further layer. This process can be seen in Figure 2-7.

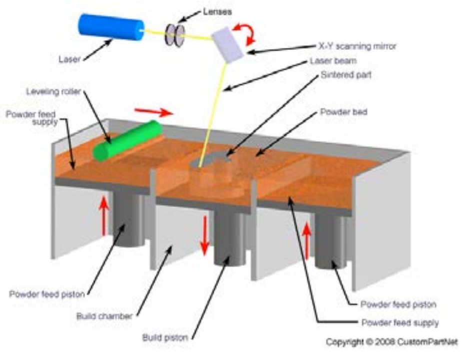

Figure 2-7 – Powder Bed Fusion Process (18)

This process is applicable to various materials, including polymers, filled polymers and metals; it is one of a few processes that allow direct manufacturing of metallic components (19). There is no need for support structures in this process as the powder is self-supporting; this allows the only post processing involved to be removing the excess powder (20). However in this process it is important to remember that any excess powder will remain inside part if an internal structure is used, therefore a hole is always required for powder removal. For this project the EOS P100 SLS machine is available for use. The part created are made from nylon, the layer thickness on this machine is 0.1mm (21) and wall sizes of down to 0.4mm are achievable (22). Due to the powder being self-supporting, the full build volume can be utilised with components even being able to be built on top of each other (23). Powder bed fused parts are often used for low volume production and for rapid prototyping metal parts. A lot of research has also been completed using Powder bed fusion for injection moulding tooling (24). SLS has many applications in a medical environment including Maxillofacial and Orthopaedic surgery, implants and prosthetic devices where unique devices that fit a human's body or injury perfectly, can be produced. This method is also very popular for light weighting aerospace and automotive components and investment casing moulds (25).

2.5.3 Material Extrusion

Material extrusion, also known as fused filament fabrication (FFF) is the most well-known form of additive manufacture and is widely available for both home use and industrial applications. The FFF machines uses thermoplastic monofilament stored on a spool and extrudes it through a pincher mechanism to retract precise amounts of filament (26). A heated block melts the filament to a temperature where it can be pushed through a pre-heated nozzle at a desired feature size to be extruded onto the modelling platform. Once a layer is completed, the modelling platform moved down by the layer thickness, and the process begins again for the new layer. This process is repeated several thousands of times to build a full part. (27) The process can be seen in Figure 2-8.

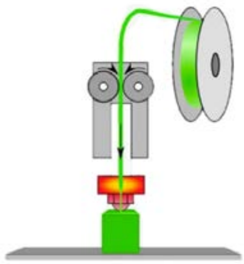

Figure 2-8- Material Extrusion Process (28)

Two different material extrusion machines are available to the group. The first being the Ultimaker II which uses PLA (polylactide, thermoplastic polyester) with a 0.4mm nozzle, that can achieve a layer resolution of 0.02mm (29). Accuracy in the X and Y axis of 0.0125mm is achievable. This machine has support structures made from the same material and therefore can be difficult to remove. The second machine available is the Stratasys FDM, this used ABS (Acrylonitrile butadiene styrene, a thermoplastic polymer) as its material. On this machine layer thickness of 0.13mm are achievable along with the same accuracy in the X and Y axis (30). This machine offers soluble support structures allowing for better part quality after post processing. FFF parts are used in a wide range of applications, as previously mentioned they are used widely as household printers, this is mostly due to their non-toxic process making them office friendly. Due the nature and brittleness of FFF parts, they are usually only used for prototyping in industry (31). Many different materials can be extruded; and novel materials such as food have featured in the public domain (32).

2.5.4 Comparisons

Each of the three processes available to the group have their advantages and disadvantages, and the Ultimaker offers the cheapest option per volume of material as seen in Table 2-1. The SLA machine offers a high resolution of 2.5microns; however is expensive when compared to the other processes available. A benefit of this process is that it offers a translucent appearance. SLS allows for the thinnest wall thickness, which may be beneficial when it comes to the shell of the drone, allows for a good accuracy and a high strength to cost ratio.

Machine	Ultimaker II	Stratasys FDM	EOS P100 SLS	3D Systems Viper Stereolithography
Cost per cm^2	£0.30	£1.25	£1.00	£2.00
Material	PLA	ABS	Polyamide (nylon)	Epoxy based Photopolymer

Table 2-1 Comparison between machines available for use

When comparing SLS and FFF process to the SLA process, SLA has the fastest turnaround time and can produce parts with the smoothest surface finish as well as the afore mentioned accuracy. This means stereolithographic parts are often used for fit and form verification testing (33). However when it comes to functional testing SLS and FFF parts use material which have approximately 80% the strength of production materials and therefore are preferred for high impact tests. As technology developed new resins which are known as 'mimics' are being developed to replicate production materials such as ABS or polypropylene (33). Powder bed fusion is the only one of the three processes that can produce metal components and requires little post processing. FFF is a cheap and safe process to use and the soluble support structures make the post processing easy but this does not improve the issues of brittleness and surface finish. The drone shell needs to be flexible and have a smooth surface to improve aerodynamics, meaning this process may not be the most appropriate.

2.6 Industrial trends

AM processes are constantly evolving as new technology is developed. The AM industry is one which is quick to react and is constantly moving with new technology. The latest development in material extrusion include parallel deposition robots, which use curved layer tools in tandem with the standard parallel system, helping to reduce the weaknesses in the Z axis which are seen in all AM parts. Improvement in the surface finish of the components is also observed (34). The latest developments in VAT photo-polymerisation processes are moving fast with patents expiring, opening up the market place for further bottom up and top down machinery. Special focus has been completed on new materials and multi-material stereo lithography processes, in bottom up machines, this offers huge benefits as not requiring full bed of resin allowing for easier material exchange (35). Huge developments are seen in power bed fusion processes, mostly around the materials that are available for use. Due to the evolution and rise of AM the need is growing for more materials to be available for printing. More interest is growing here as the average cost of powdered polymer materials is 20 percent more than the equivalent injection moulded grade (36). New developments can be seen in Tissue Engineering within the Biomedical Industry, where new materials are being developed with the aim of making three dimensional scaffolds which guide cell growth whilst regenerating tissues or organs within the body (37). It is a very exciting time at present for AM, new processes and developments are constantly occurring and there is no sign of a decline in interest in the near future.

3 Literature Review on Reverse Engineering

The 3D scanning industry is progressively growing increasing at around 15% annually since the year 2013 and is estimated to be valued at $4 billion by the year 2018 (38). Since the new millennium, not only has industrial scanning progressed but also consumer, this is due to advances in 3D printing technologies and products such as Microsoft Kinect along with 123D catch which can all be used for reverse engineering capabilities.

Reverse engineering is a method used to gain a further understanding of the fundamental workings of a product or object. The broad term that can be applied to multiple areas of engineering analysis, such Electronics, Geometry of mechanical parts, Software, Chemical composition and Materials. There have also been some cases in which it has been used to reverse engineer patents or ideas which were not publically released (39).

The general process for Reverse Engineering object geometry is shown below in Figure 3-1.

Data Acquisition → Data Processing → Output Data

Figure 3-1 the general process of reverse engineering for geometry.

Data acquisition – The method used to obtain the data of the object that is being analysed.

Data Processing – The process in which all the data points or layers are collected and combined together in order to create a useable model.

Output – The visualisation of the data obtained from the 3D model, typically CAD or a surface model.

Reverse engineering has many uses as it creates a digital copy/back up of real world objects, it can also be used for objects that may be difficult to model such as human body parts or bespoke artworks/sculptures.

3.1 Data Acquisition

Data acquisition is the first stage in reverse engineering. The types of scanning techniques used to obtain information can be broken down into 3 categories; contact, non-contact and volumetric. It is critical that the object being scanned is analysed in order to determine the most suitable method of scanning, the following points should be considered when selecting scanning methods:

- The material it is made from; as some materials may affect how much light is reflected.
- The size of the object; portable scanning methods are available to scan large objects such as buildings, cars or aeroplanes.
- If the object can be held still; objects that may move such as a human may need additional reference points to improve the accuracy of data acquisition.
- If the object can be disassembled further into smaller components.
- Speed of the scan required.

Currently there are many methods that can be used to obtain the geometric data; they typically fall under the 3 categories (Shown in Table 3-1).

Contact	Non-Contact	Volumetric
• Touch Probe	• Laser Trigger	• Destructive RE
• Hard Probe	• Laser Strip	• CT Scanning
• Drag Probe	• Structured Light	• MRI Scanning
	• Photogrammetry	

Table 3-1 Types of geometric scanning methods.

3.2 Contact Scanning

Contact scanning is a highly accurate method typically used at the end of manufacture when parts are inspected for tolerance analysis. Probes are attached to a moveable machine; this can either be automated or manual, however the probe must be in contact in order to store co-ordinate measurements of the objects geometry. Typically, there are 3 types of contact probes:

Touch probe: The probe functions on a co-ordinate measuring machine (CMM) by moving it until the probe tip is in contact with the object being scanned, once in contact the position co-ordinates are stored.

Hard Probe: are placed in contact manually by an operator and the co-ordinate points are stored when a button is pressed. They are relatively low cost and accurate (less than CMM), however provide low density of data points, they are slow and operator sensitive (40).

Drag probes: are in contact with the surface and dragged across whilst the deflection of the probe is measured to obtain the geometry co-ordinates, it is generally faster and provides a higher point density however, it is expensive and less robust than other methods of scanning (41).

Currently touch probes are relatively slow in data acquisition; they also are not well suited when scanning surfaces of objects. However, surfaces can be reconstructed in CAD. The probes themselves can have access restrictions due to the diameter and another drawback is that they must be in contact with the object that is being scanned. However, companies such as Renishaw provide low cost and accurate probes, therefore meaning this technology is a relatively accessible and affordable method of reconstructing geometry (40).

3.3 Non-Contact

Non-contact methods typically work using lasers or cameras in order to scan the geometry of an object.

Triangulation – this method works on the theory of triangles, the angle at which the laser is relative to the receiver is known and also the distance between them is. When the laser hits an object of a different height it will reflect (initially through a filter then a lens) to a different part of the sensor, hence the height of the object can be calculated. Typically, a laser strip is used to increase the amount of data points that are collected and also the speed of acquisition. A recent analysis of triangulation was conducted to create a device that could be fitted to a CMM in order to quickly measure the soft tissue of a person's forehead to an accuracy of 0.16mm (42).

Time of flight - The time taken for the laser to reflect off the object along with the position of the laser is used to calculate the distance of the object being scanned in order to produce a point cloud; however, this method is relatively slow. It can be used for short range this technique has been used in many industries to scan architecture, for example the company Direct Dimensions have scanned many historic monuments in America such as the Lincoln

Memorial statue after September 11 2001. This was achieved using a portable long-range laser scanner to scan the entire building with an accuracy of around ±6mm (43). Further examples of scanning can be shown in Direct Dimensions case studies (44).

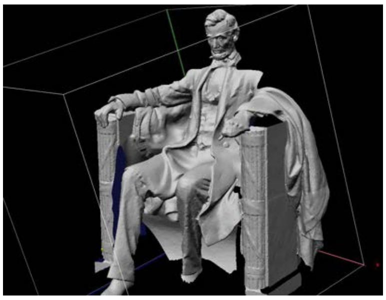

Figure 3-2 the 3D modelled data of the Lincoln memorial statue (43).

Structured light – This method involves light strips (typically white or blue light) being projected on the geometry, the shape of the geometry causes the light strip to become distorted, a CCD camera then captures the image of the distorted line. Geometry can next be calculated from the distorted light strips. For multiple scans, reference stickers or photo are typically used to merge the scans together as a point of reference (41). It should also be noted that structured light can be affected by ambient light conditions.

Although currently the resolution of scanning is relatively low, recent studies from MIT have found innovative ways of improving the scan depth of Microsoft Kinect system, by using a new technique called polarised 3D the Kinect system is able to get a much more accurate depth scan and theoretically increase commercial 3D scanners by a factor of 1000 (45).

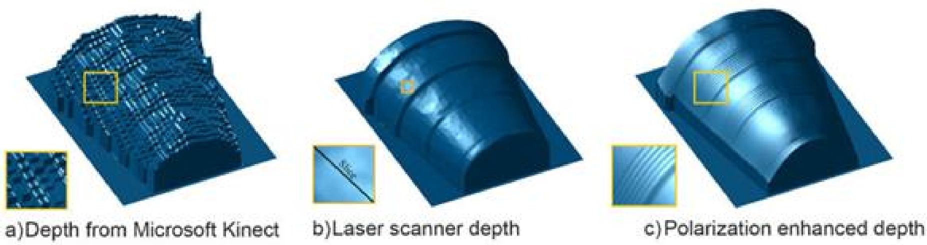

Figure 3-3 shows the improved scanning technique using polarised 3D.

Photogrammetry –Images of the geometry are captured at different angles, these images can then be used to calculate the geometry. Development of this camera system may be included in next generation smartphones which will enable users to have cheap access to scanning system, it is also suggested that the use of 2 cameras on a smartphone could lead to increased biometric security combining facial recognition scanning with fingerprint scanning (46). Currently, apps such as 123D catch by Autodesk allow users to scan objects with smart phones; however testing and investigation by Loughborough University has determined that whilst useful the software does not provide high accuracy models replication as of yet (47).

3.4 Volumetric

In order to gain information about the inside of geometry volumetric techniques can be used, some methods are destructive whilst others are non-destructive, these methods are briefly summarised below as they use the same principles as the previous methods (e.g. time of flight, triangulation):

Destructive RE – This method is useful for reverse engineering small and complex objects in order to gain a better understanding of internal and external features. The method simply uses a CNC machine in combination with a CCD camera, in which images are taken of each layer that is machined away. Although destructive engineering destroys the object being measured, it is a fast and accurate technique which can gain typical accuracies of ±0.0127mm (48) and work with many metallic materials.

Computed Tomography (CT): is another type of Non-Contact active scanning, this method however uses multiple X-rays in order to gain sliced images of an objects internal structure. Currently the usage of this scanning method has increased more than 3 times since 1993, with some estimates of approximately 70 million scans annually being conducted (49).This technology can be used to rapidly diagnose patients for injury or cancers without invasive surgery. However, the technology itself is relatively expensive and uses radiation in order to scan objects; hence making it harmful to humans in high doses (50). Currently, the accuracy of High resolution computed tomography is relatively high and takes slices of around 1-2m. The accuracy is affected most by the field of view used for the image, hence why the majority of scans will be focused on one key area to maximise resolution (51)

Magnetic Resonance Imaging (MRI): Similar to CT scanning, this method takes individual slices of the object in order to build up a 3D model of the scanned part. However, this method does not involve the use of radiation to gather the data points. Typical manufacturers of MRI scanners are GE, Siemens, Hitachi, Philips and Toshiba. Recent costs of this technology are slowly declining with some systems such as the Airis II costing around $175,000 (52). However, the running costs involved in cooling the superconductive magnet can be a large disadvantage to this particular method of reverse engineering.

3.5 Data Processing

Typically, the scanning methods will yield data in the form of point clouds or layers which may be made up of thousands of co-ordinates and may have multiple reference co-ordinates. These data points are commonly converted to an STL file format using algorithms which best fit the data even if there may be occlusions involved in the scanning process as shown in the report of generating 3D building scans with potential pedestrians or other objects in the way (53).

As the raw STL files are generally very large from scanning the object they are further processed to reduce the number of triangles. Noise sources which can be caused from vibrations and reflections can also be reduced through filtering.

3.6 Data Modelling

The final STL file can be used in order to recreate geometry in CAD packages, such as NX and solid works which are both very capable of handling large STL files. Solid works particularly offers reverse engineering tools such as ScanTo3D, Surfacing Tools which specialise in recreating the imported data to native solid works files; this allows the user to easily edit and modify the existing design of the scanned object (54).

It is clear to see that reverse engineering data capture in combination with data modelling software is a very useful tool in the modern world of engineering. The technology is continuously developing at a rapid rate (in terms of accuracy and cost reduction) in both industrial applications and also consumer applications. The applications for this process will be greatly beneficial in the smartphone and virtual reality industry which is currently in its infancy and is expected to see a large economic upturn in upcoming years.

4 Audio Review

As outlined in the introduction, audio will be an added functionality to this product, therefore it is important to understand the fundamentals of achieving good audio quality within the drone itself. The following points should be taken under consideration when combining a drone with a speaker for this reverse engineering application (55):

- For low frequencies, the speaker must be able to have air intake, hence why the majority of hi-fi speakers have intake ducts in the rear.
- The driver itself should also be mounted securely to ensure that the speaker does not rattle and create distortion which can greatly affect the sound quality.
- The speaker should not be mounted in too large or too small an enclosure as these can act negatively towards the sound quality.
- Ideally a speaker can have different channels for the different frequencies i.e. a bass, mid and high end speaker which is suggested to improve the range of the audio.

As the speaker is also going to be mounted onto the drone there will be background noise from the drone itself due to the propellers, therefore the speaker should be mounted facing downwards towards the user to provide the best audio experience. It should also be noted that sound cancelling technology (Active Noise Control) could be incorporated into a product like this, in which inverse frequencies to the drone's propellers could be played through the speaker to reduce the noise effect of the propellers themselves (56) shown below in Figure 4-1 (57).

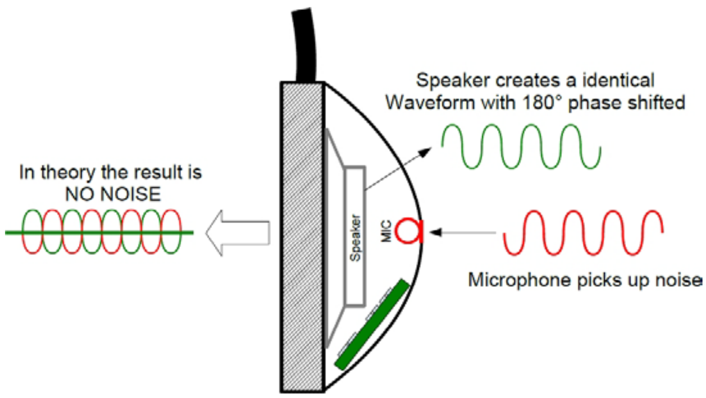

Figure 4-1 example of noise cancelation in headphones.

5 Disassembly & Analysis

5.1 Syma Quadcopter Review

As discussed earlier the drone that is disassembled is the Syma Quadcopter, which retails at £35 from amazon UK. The drone comes with stabilised flying sensors and also image capturing capabilities, however the aim of this project is to add further features to product without removing the functionality; hence it is reviewed in this section.

Figure 5-1 the Syma Quadcopter analysed for this project.

The drone was initially analysed; this would therefore allow the group to determine where improvements should be made to the drones' current design, the following key points were observed during this testing:

1. Flight testing

Before disassembling this product, it was initially flown by each of the group members in order further develop an understanding of the products functionality. This included flying the drone indoors and outdoors thus exposing it to many flying conditions.

2. Secondary flight functions

During the flight, it was found that the drone featured extra functions such as barrel roll and spinning. It was also found that in windy conditions, this flip function was unable to perform well due to the non-spherical shape of the drone. Hence, as it rotates its wind resistance increases due to the increase in surface area.

3. Camera

The camera of the drone is relatively small and light in weight. It can be detached or added by the user and weighs a total of 10g, it is important that camera is securely attached to the drone, and the current design is not the most secure fitting. This could be further improved in the redesign by building it into the shell of the drone.

4. **Identifying forward position from lights**

Whilst flying the drone, it was found that often it was difficult to determine which way the drone was facing, this sometimes confused the user as the drone would fly in different and almost random directions. This could be improved by moving the lights on the drone to give feedback to the operator.

5. Feet's ability to prevent damage

The feet designed in this drone are made of a relatively robust and flexible material which is crucial in the protection of the drone during landing, or if the operator mistakenly drops it.it is also there in order to level the drone on the first power up; as this is where the drone calibrates its accelerometer for the flight.

6. Unstable flight in high winds

The drone struggled to maintain a steady flight path during windy conditions. This is likely due to the aerodynamics of the product (and potentially weight), therefore CFD Simulation will be used to further analyse is.

To summarise, the redesign will focus on improving the aerodynamics of the drone, whilst also keeping critical features such as the feet for calibration, the camera, visual orientation feedback and also the extra flight functionalities (barrel roll and twisting).

5.2 Syma Quadcopter Disassembly

The Quadcopter was disassembled into its primary components which consisted of following components shown in Table 5-1.

Part No.	Description	Quantity
01	Upper Body	1
02	Lower Body	1
03	Rotating Blade	2
04	Reversing Blade	2
05	Protecting Frames	4
06	Battery Cover	4
07	Rotating motor	2
08	Receiving Motor	2
09	Motor Holder	4
10	Lampshades	4
11	Light boards	4
12	Receiver Board	1
13	Battery	1
14	Battery Cover	1
15	Gear	4
16	Landing Skids	2
17	Camera	1

Table 5-1 the primary components of the drone.

There were a total of 40 components inside the drone (not including the screws), which meant that the overall disassembly time was relatively long and also counter intuitive. There were a total of 44 screws involved in taking this apart, which is more than the total part count; it should be noted however, that this number may be high as the drone could potentially fall from large heights; hence components need to be held securely in place. The majority of screws were used to hold the two shells together. This could be improved by creating a lip around the edges of the shells so that the material aids in the assembly and also increases the strength. This would also reduce the overall assembly time of the product which would in turn, reduce the costs of the product and increase the company's profits overall.

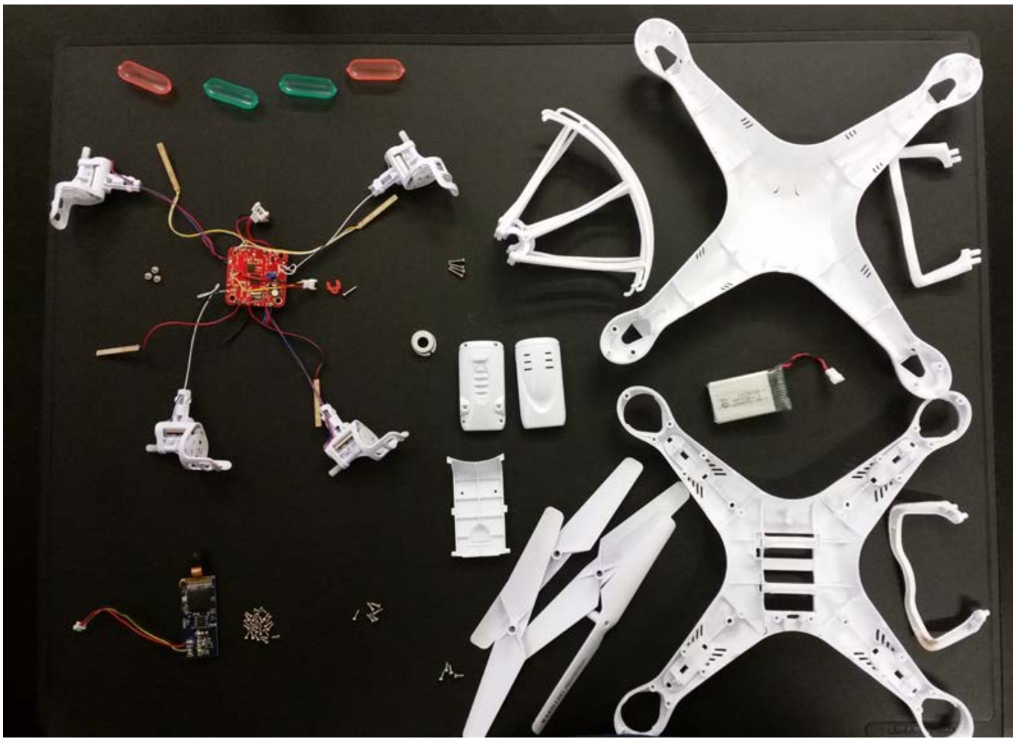

Figure 5-2 a view of all the components inside the drone.

5.3 Design for assembly/disassembly

A further consideration for this product is to improve the overall assembly performance of this product. By using Boothroyd Analysis (58), it can be clearly identified that the amount of screws in this product greatly affects the overall assembly time. This method of analysis also identifies that the amount of components needed to assemble a product should be reduced. For example, the motor holders could be combined with the lower shell in order to reduce the part count by 4.

Further assembly time reduction can also be seen in the shell, this currently uses 24 screws in order to attach the two shells together, and this assembly could be vastly improved by using snap fittings in the new design of the drone. It should be taken into consideration however, that some screws should still be used in order to prevent the shells from coming apart on impact (i.e. if the operator crashes the drone).

These assembly considerations will be taken forward into the final design of the drone.

5.4 Bluetooth Speaker Review

Following on from the decision to add a speaker to the drone and the previous speaker research the group purchased a Freecom tough Bluetooth speaker as seen in Figure 5-3. The battery within the speaker allows for 7 hours of music play and the speaker can play music wirelessly via Bluetooth. (59)

Figure 5-3 Freecom Bluetooth speaker

Bluetooth Speaker Disassembly

The speaker was disassembled to allow for the required parts to be identified, Figure 5-4 the disassembled product and Table 5-2 shows the part count.

Figure 5-4 - disassembled Bluetooth speaker

Part No.	Description	Quantity
01	Speaker and PCB	1
02	Lower casing	1
03	Upper casing	1
04	Speaker grill	1
05	Screws	6

Table 5-2 Part count for Bluetooth speaker

The speaker and PCB with integrated battery and Bluetooth receiver are the only parts of the Bluetooth speaker which will be used within the final drone prototype. These parts can be seen in Figure 5-5

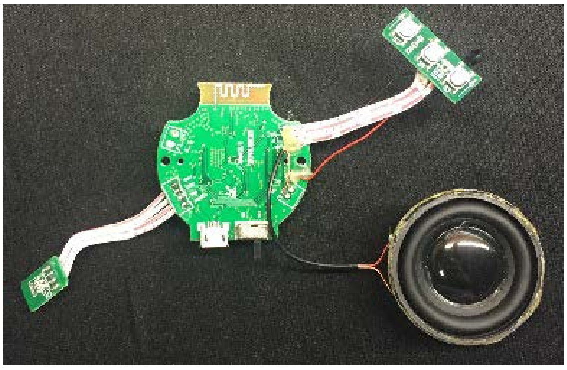

Figure 5-5- Required parts from Bluetooth Speaker

Range testing was also completed on the speaker to ensure it would have enough reach for the when the drone is flown. The result shows that the range exceeded 40m from the Bluetooth enabled device sending the music. The range of the drone is 50m therefore it is deemed this speaker is adequate. The range of Bluetooth depends on the class of device used, class 1 devices are quoted to have a range of 100m and therefore in production a speaker with a class 1 range could be sourced. (60)

6 Generating CAD file from RE technique

6.1 Syma Quadcopter

In order to help facilitate the redesign of the drone, all component dimensions were measured and used to generate CAD models for later use in an assembly. The upper and lower shells, flexible feet and both Printed Circuit Borads (PCB) were measured using a planar optical CMM. The software used for the machine supported shape recognition and shape fitting algorithms which were used to measure the diameter of the screw holes. Using the software and CMM, the shell screw holes in one quarter of the drone were measured as well as the PCB location pin and holes. The drone shells were placed on the optical CMM as seen in Figure 6-1 with background illumination dependant on the lighting conditions in the room.

Figure 6-1 - Upper shell (left) and lower shell (right) of the Syma quadcopter in the orientation it was used on the planar optical CMM

The planar optical CMM was perfect for the shells and drone feet as these parts were flexible and unsuitable for measuring using typical contact methods. The benefit of using this method for the PCBs was that the shape fitting tools could be used to measure the diameters of the complex geometries in the speaker PCB and the locations of the holes in the drone PCB. The speaker PCB and dimensioned CAD model can be seen in Figure 6-2. The drone PCB had not been manufactured with perpendicular edges and the holes were not parallel with the PCB edges so the optical CMM proved to be very useful in helping establish the critical dimensions on the board and referencing parts to the holes. As there were many components on the PCB, they were not individually measured as it was intended that there would be a large cavity between the PCB and walls of the drone to promote airflow over the circuitry. The hole dimensions on the PCBs were verified using pin gauges. The simplified drone PCB can be seen in Figure 6-3. It can be seen that the capacitors, holes, and maximum PCB width have been measured as these were deemed 'critical' dimensions.

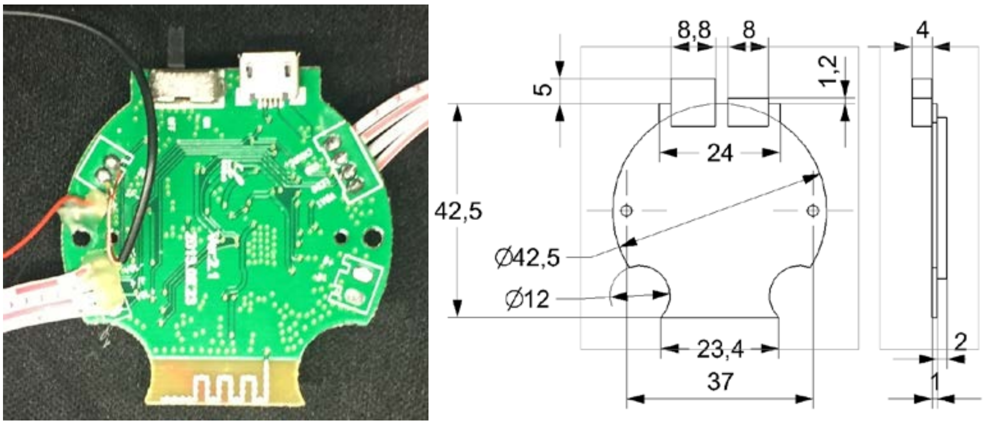

Figure 6-2 - Speaker PCB dimensions after measuring with the planar optical CMM

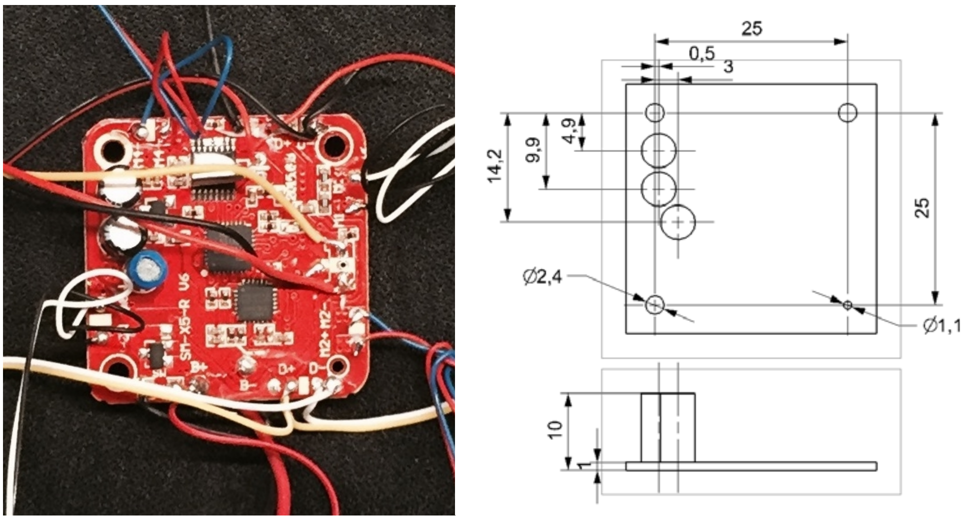

Figure 6-3 - Simplified CAD geometry of the drone PCB

High parts that were susceptible to perspective error or parts that were difficult to balance on the optical CMM were measured by hand using a Vernier calliper or micrometer. Radii on the parts were measured using a radius gauge. Parts that were measured in this way include the motor holders, camera PCB, on/off switch, batteries, LED strips and camera unit. It was imperative that dimensions on the motor holders were accurate so the new drone could be designed to have minimal clearance between faces of the parts and ensure there was no deflection when the components were fitted together. Figure 6-4 shows the drone motor holder and the dimensions measured. Inter component connectors were also measured to ensure that the components would still connect o each other when assembled within the new drone design.

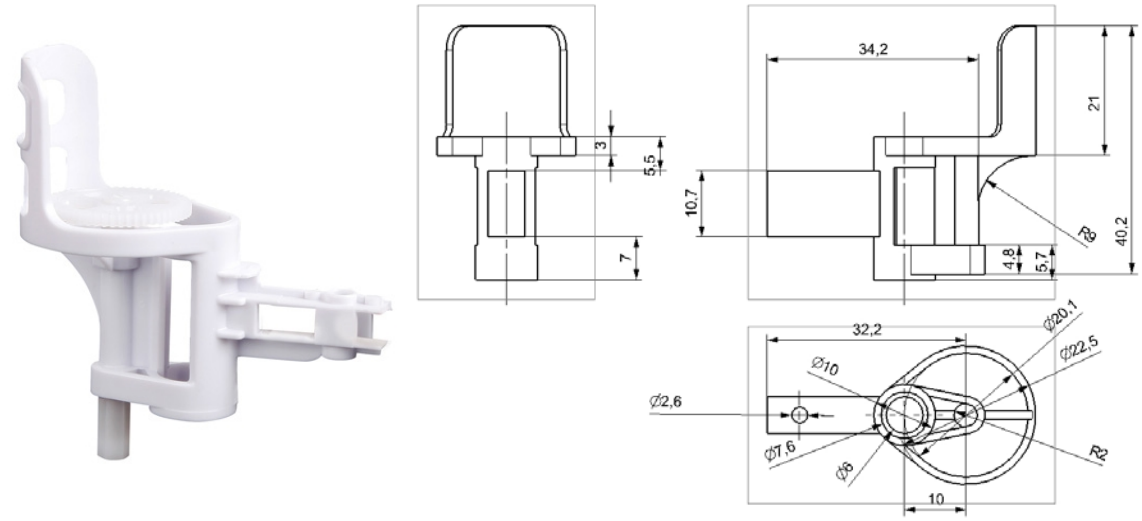

Figure 6-4 - Drone motor holder and 'critical' dimensions

Multiple attempts were made to use a Z Corp. ZScanner, capable of measuring objects placed on a surface with reference points. Due to the extremely fine nature of some of the components, it was very difficult to obtain a useable .stl file from the scanning sessions. However, after several sessions scanning a quarter of the drone in different orientations, multiple .stl files were combined in AutoDesk MeshMixer to create the full model seen in Figure 6-5

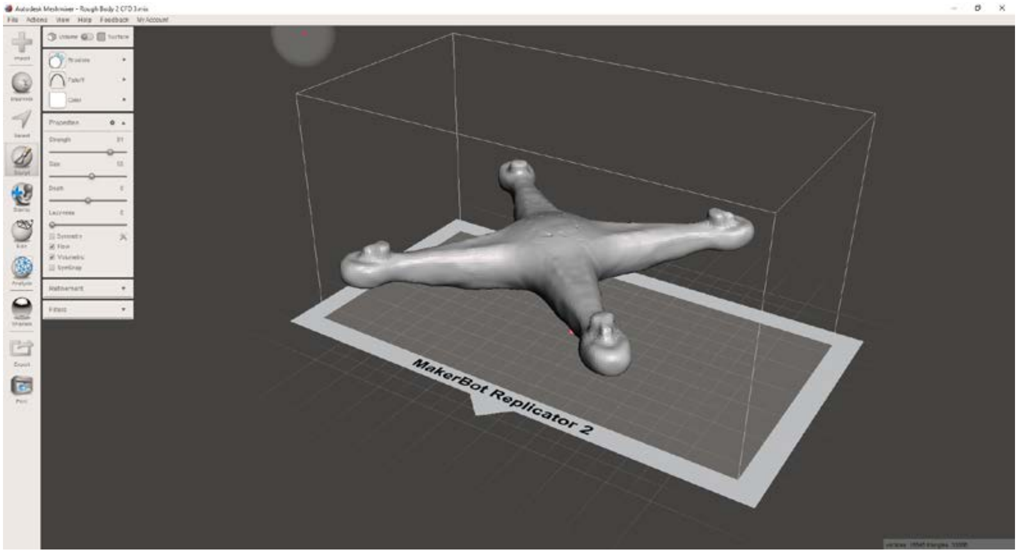

Figure 6-5 - Multiple combined .stl files to create one full model of the Syma quadcopter

The quality of the model was quite poor, even at high cell density due to the limitations in using the ZScanner. It was a consensus within the group that the scanner did not possess the definition and accuracy that was expected for such a small measured part. The program is surprisingly powerful for free software and many variables within the geometry could be adjusted with relatively little computing power.

In order to establish a comparative study between the current quadcopter and future designs, a simple simulation was performed in StarCCM+ with the drone at a 30° incline, representative of the incline experienced by the drone when flying forward, backward or strafing.

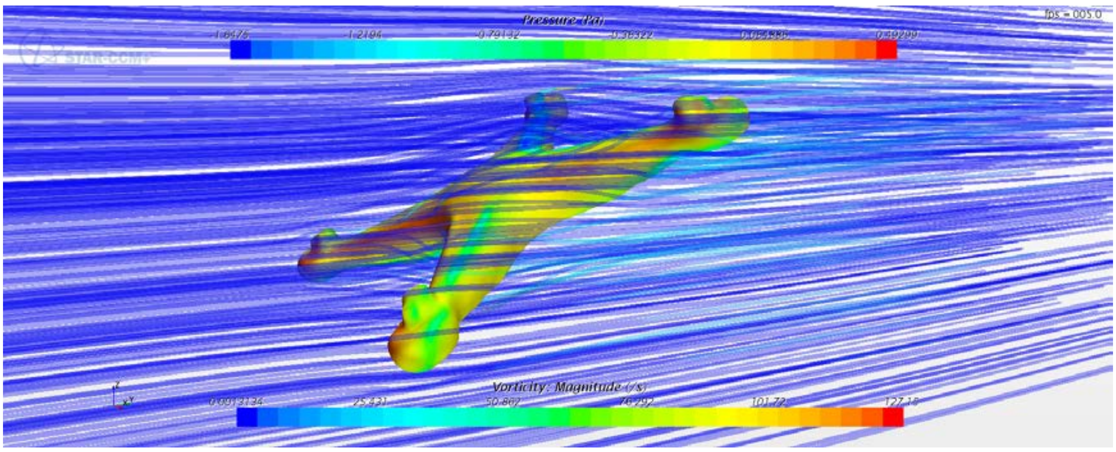

Figure 6-6 – Simulation showing vorticity streamlines and surface pressure on the Syma quadcopter

It can be seen that there are high concentrations of pressure along the bluff body of the drone whilst in flight, which can cause instability in flight and reduce the speed at which it can traverse. Figure 6-7 shows a side-on scalar representation of the heavy vortex regions trailing the drone. These extend quite far behind the drone, and cause large amounts of wake drag. This is likely to be caused by the flat surface at the base of the drone. There are also high vortex concentrations at the protrusions on the arms due to the sudden change in geometry.

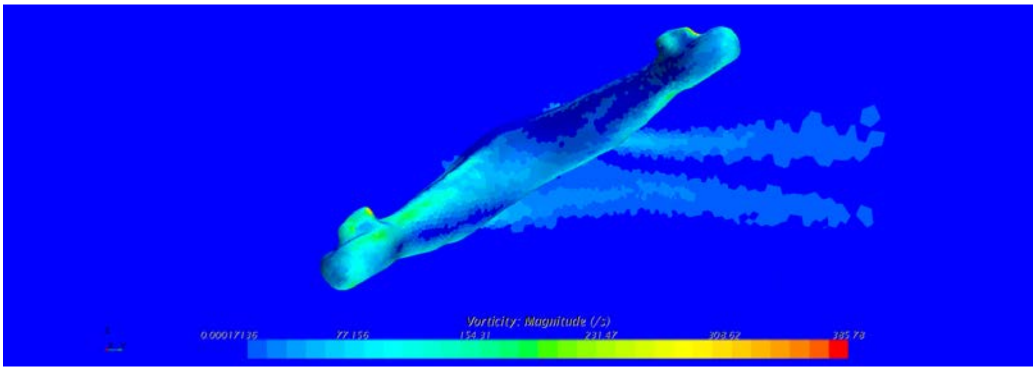

Figure 6-7 - Simulation showing vorticity scalar across the body of the Syma drone

The simulations have given some qualitative (and when validated, quantitative) feedback on the design of the current drone and potential areas of improvement.

6.2 'Darth Drone' Redesign

With all components measured and digitised into CAD models, the design of the new drone could commence. Drawing inspiration from popular video games such as Portal 2 and the Star Wars universe (Figure 6-8), an axisymmetric quadcopter was produced using a bottom-up approach to the design process.

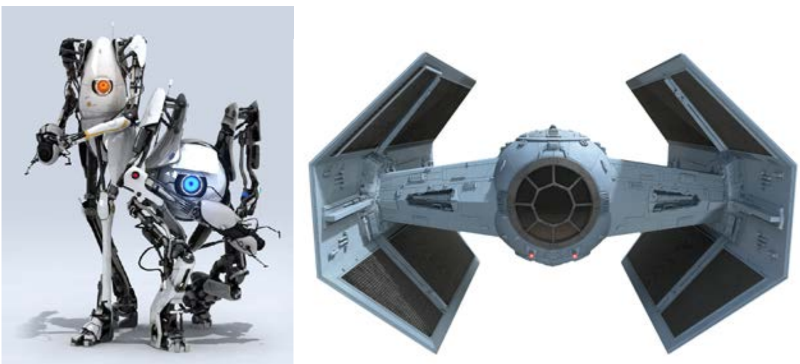

Figure 6-8 - ATLAS and P-body (left) from the Half-Life universe and the TIE Advanced x1 from the Star Wars universe. Images reproduced from (61) and (62) respectively.

The drone design can be seen in Figure 6-9. It is immediately apparent that the main body of the drone is larger but significantly more rounded in its design. The outside of the shell has slots in the arms for the motor holders to locate in, holes for the original feet to slot into and a protective grid across the speaker face similar in design to the TIE Advanced x1's front face.

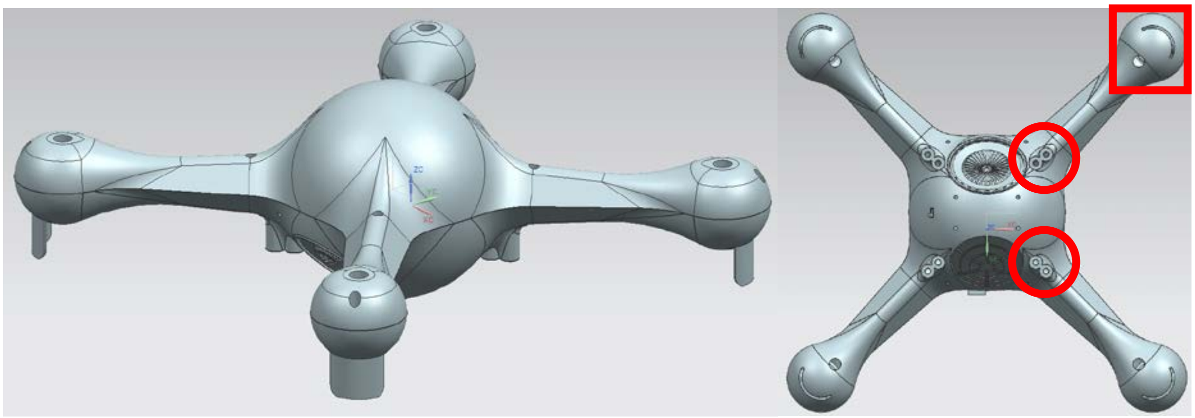

Figure 6-9 - Isometric and bottom view of the proposed drone design. The holes for the feet can be seen in the circles and the slot for the motor holders can be seen in the square.

A close up of the speaker guard can be seen in Figure 6-10. Using the research gathered in the literature review, the guard was designed so to provide maximum protection against impact whilst not degrading the audio quality.

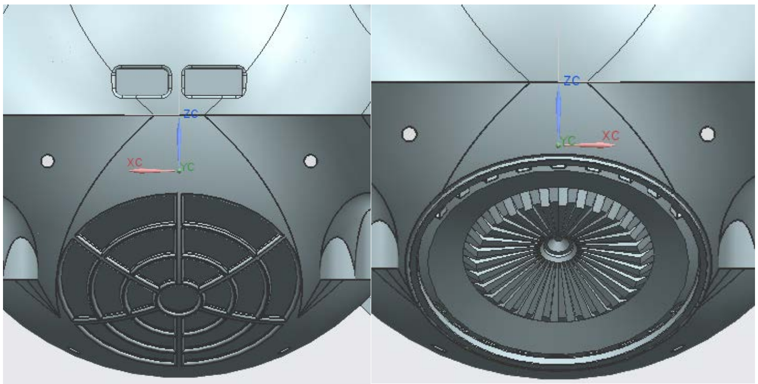

Figure 6-10 - Close up view of the speaker grating and the camera unit

It was decided to move the LEDs from the arms of the drone, and incorporate them into the camera unit as directional lighting. The unit that contains the camera unit was based on the digital iris design in the ATLAS model from Portal 2. By incorporating channels and pedestals in the rear of the part, the LEDs could be mounted to shine through the part, illuminating the region being captured. This is assuming the part is made using Stereo lithography (SLA). Figure 6-11 shows the designed part with spaces for mounting the LEDs and camera unit.

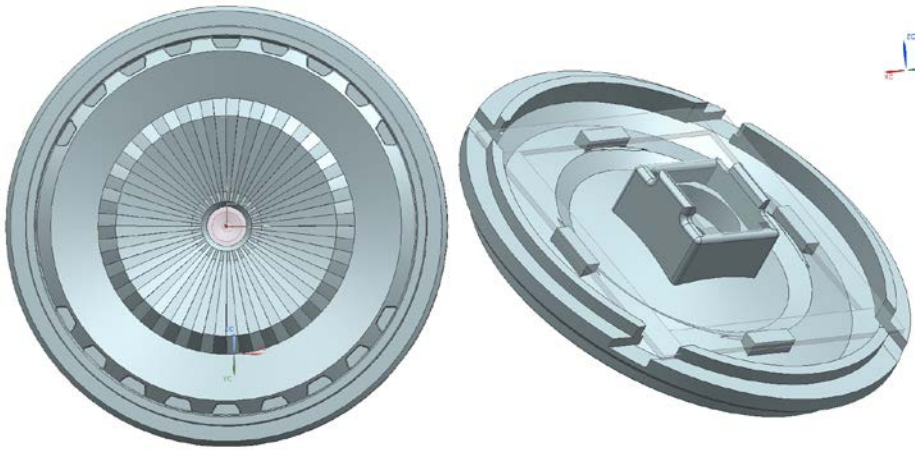

Figure 6-11 - Camera mounting component

The bottom-up design process utilised the previously created CAD models of the internal components to help create a general layout of the drone interior. With the components in place, the drone body could be constructed around the PCB, motor holders and speaker system, and then shelled to create a final structure suitable for printing. During the design of the drone, both halves had to be created concurrently in order to ensure no collisions occurred between components within the body. The bottom shell (Figure 6-12) contains the speaker, camera PCB, motor holders and batteries for the components. Pillars and webbing were inserted between the shells and in the arms to provide some rigidity and support for joining both shells.

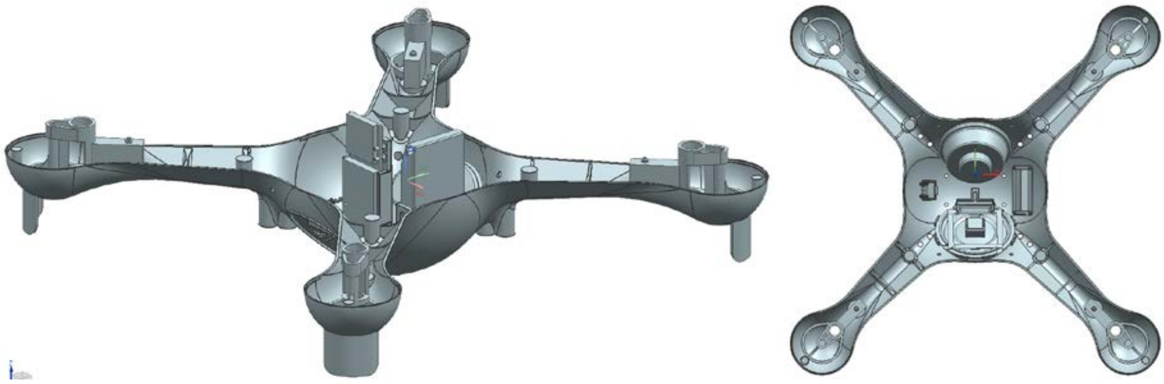

Figure 6-12 - Bottom half of the proposed drone design, highlighting the screw studs, battery holder and camera PCB pillar

The top half of the drone contains the PCBs for the speaker and drone. They have been designed to sit proud of the body, ensuring adequate cooling across the part. The speaker

PCB was designed to protrude from the top shell so that it could be turned on and off from outside the body, without the need to disassemble the unit for charging.

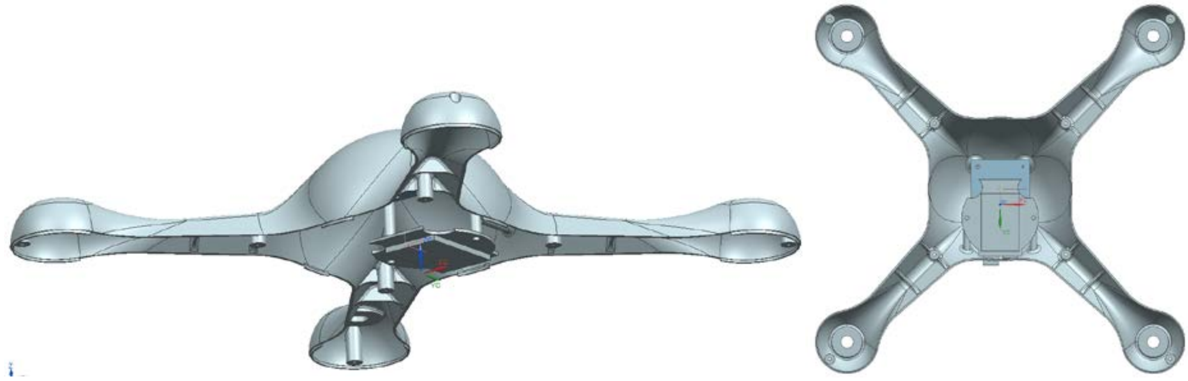

Figure 6-13 - Top half of the shell showing the PCB locations and webbing

Whilst designing the new drone, attention was paid towards the overall weight of the unit, based upon the maximum flying weight of the Syma drone with additional masses. The calculations dictating shell thickness can be found in the Appendix. The ability for the prototype to fly was seen as a secondary objective when designing the drone as this redesign was conducted primarily to highlight the introduction of a speaker system. The mass of the drone was monitored and adjusted to improve the probability of flight but not to cause detriment in the manufacturing process.

As before, a CFD simulation was conducted on the new design to identify any areas of aerodynamic improvement. Figure 6-14 shows the streamlines and surface pressure along the surface of the new drone. As seen, there are no longer any high-pressure concentrations along the front edge of the drone due to the rounded design. There are points of stagnation on the tips of the arms but this is due to the nature of fluid flow against spherical bodies.

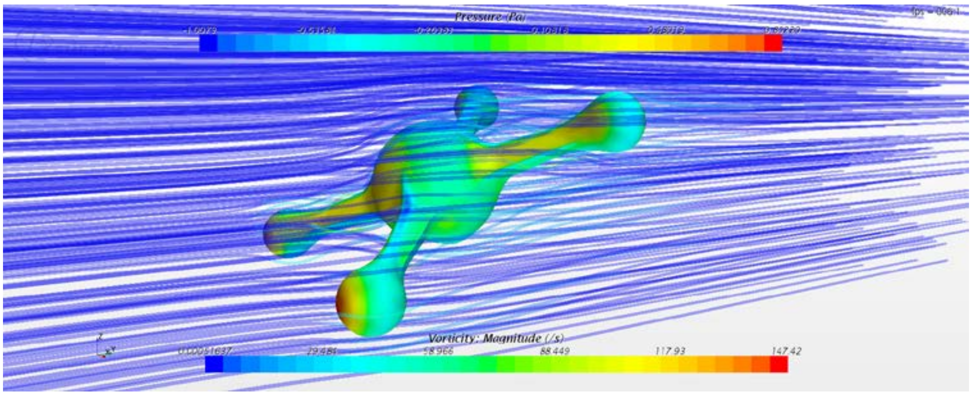

Figure 6-14 - Simulation showing vorticity streamlines and surface pressure on the redesigned quadcopter

Again, by observing the vorticity scalar across the body of the drone, it can be seen that there is a distinct reduction in the length and width of the pressure wakes. This suggests that if the drone would fly, it may perform better in terms of stability and speed if the power to weight ratio was matched to the original design.

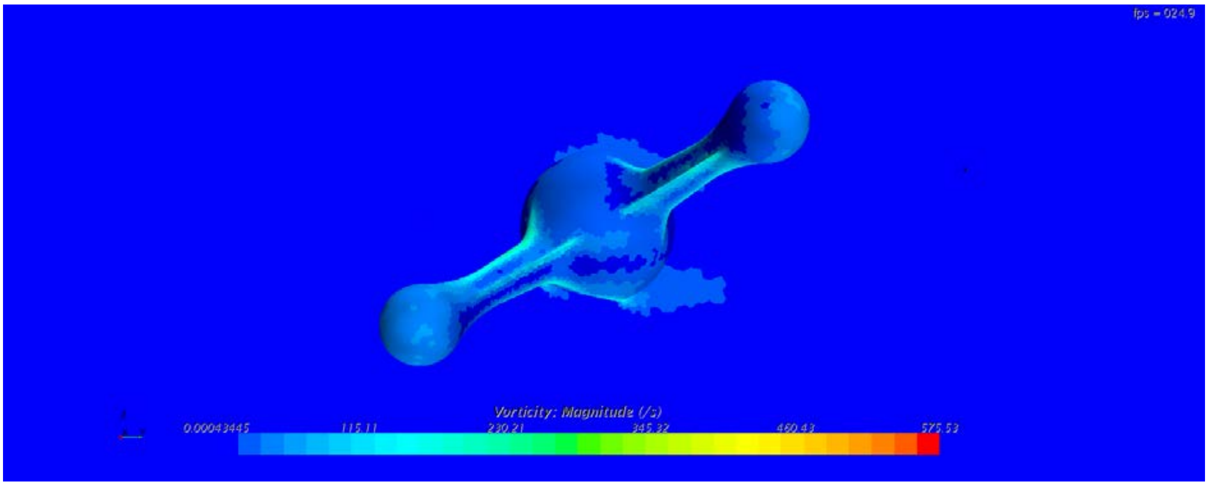

Figure 6-15 - Simulation showing vorticity scalar across the body of the redesigned drone

7 Manufacturing Report

From the CAD generated for the re-designed drone a manufacturing plan is required. This includes which AM processes have been selected for each part along with the overall manufacturing cost. With references to the calculations in the appendix the three parts that are to be manufactured are shown below.

7.1 The top and bottom shells

The top and bottom shells as seen Figure 7-1are to be manufacture via Powder bed Fusion (SLS in this case). There are many reasons why this manufacturing process has been selected, the previous literature review on additive manufacture have helped to make this decision.

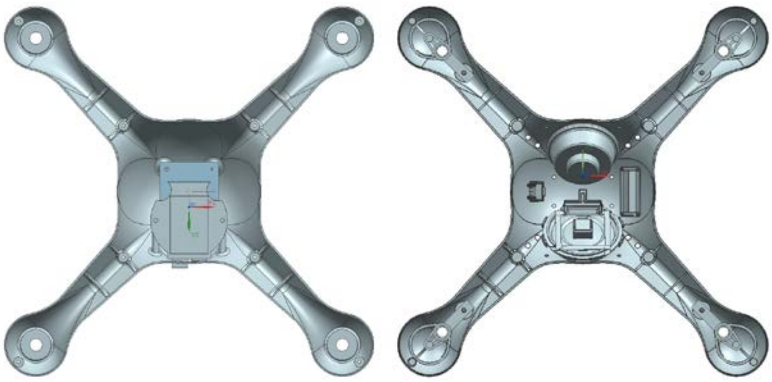

Figure 7-1 top and bottom shells of the drone.

- SLS parts have a good quality surface finish leading to good aerodynamic properties.
- SLS parts have a good level of flexibility in parts further allowing for aerodynamic properties.
- SLS parts can have a wall thickness down to 0.4mm, this allows for the thickness of the wall to be as close to the original part as possible.
- Due to SLS process there are not support structures required, this due the powder bed being self-supporting and therefore a better surface than material extruded parts can be produced, also undercuts in the product can be included.

- Finally due to SLS parts having a layer of porosity the weight of the component should be less than that calculated.

These parts represent the majority of the cost of the prototype at £50.29.

Figure 7-2 below shows the final produced Shells.

Figure 7-2 the final produced shells.

7.2 Iris

The iris is the part of the drone which sits in the lower shell as seen in Figure 7-3. This part is to be manufactured via the VAT polymerisation method (SLA in this case). Following on from the literature review, there are many reasons why this process has been selected.

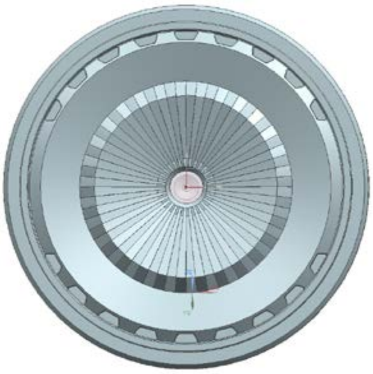

Figure 7-3 the iris of the drone.

- SLA parts have a level of translucency, this is key to the design as lights will be shined through this iris to signify the power and different modes of the drone. This is the main reason for selecting this process.
- SLA parts also have a smooth surface finish, further benefiting the aerodynamic properties of the prototype.
- SLA parts also have a very high accuracy and high resolution resulting in little tolerance needing to be left to ensure a good fix between the Iris and bottom shell/

This part represents a low overall cost despite being the most expensive process available to the group; this part came in at a total cost of £10.67. Due to down time of the 3D Systems Viper machine, this part could not be created on time, which can be seen in later images of the assembled drone.

The predicted cost of the whole drone is £60.96 and the weight is 60.5g, full details of the breakdown can be found in the appendix.

8 Results and Discussion

The fully assembled, redesigned drone can be seen below in Figure 8-1. Sadly, due to machine downtime, the SLA part for the camera was not completed in time for the report despite the .stl files and CAD files being submitted on the 18th of April 2016, in the first week of manufacturing.

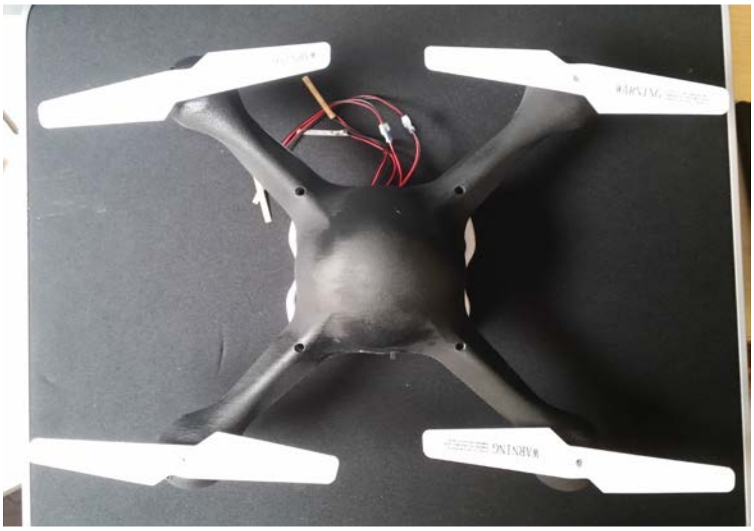

Figure 8-1 - The fully painted and assembled 'Darth' drone

The internal wiring with removable connectors can be seen below in Figure 8-2. Poka-Yoke theory has been applied here so that the batteries cannot be connected to any other port on the PCB other than the power supply. The connectors have had to use very long wires due to the assembly process for the drone. Ideally, these wires would have been shortened to reduce the amount of weight on the drone.

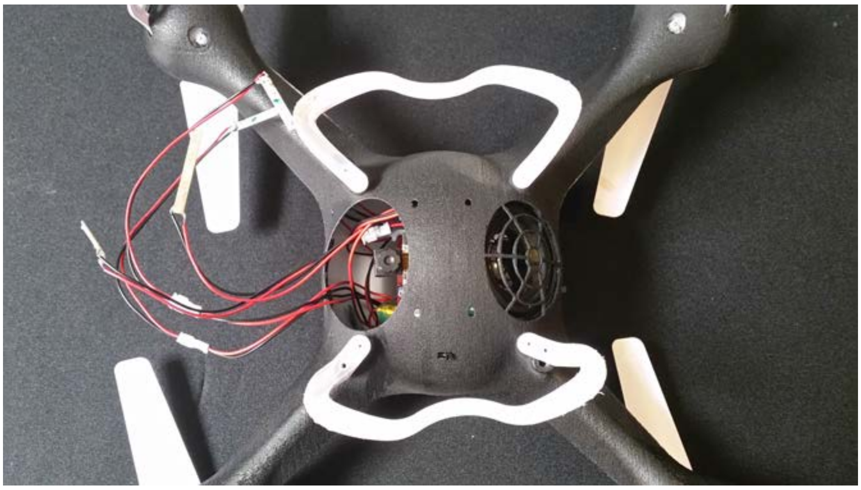

Figure 8-2 - Internal wiring and PCBs in the drone

If the camera housing part had been completed, the LEDs would have shone through the translucent material to illuminate the capture area. In order to prevent glare into the camera, the iris would have had an internal coating to prevent diffraction of the light into the camera lens.

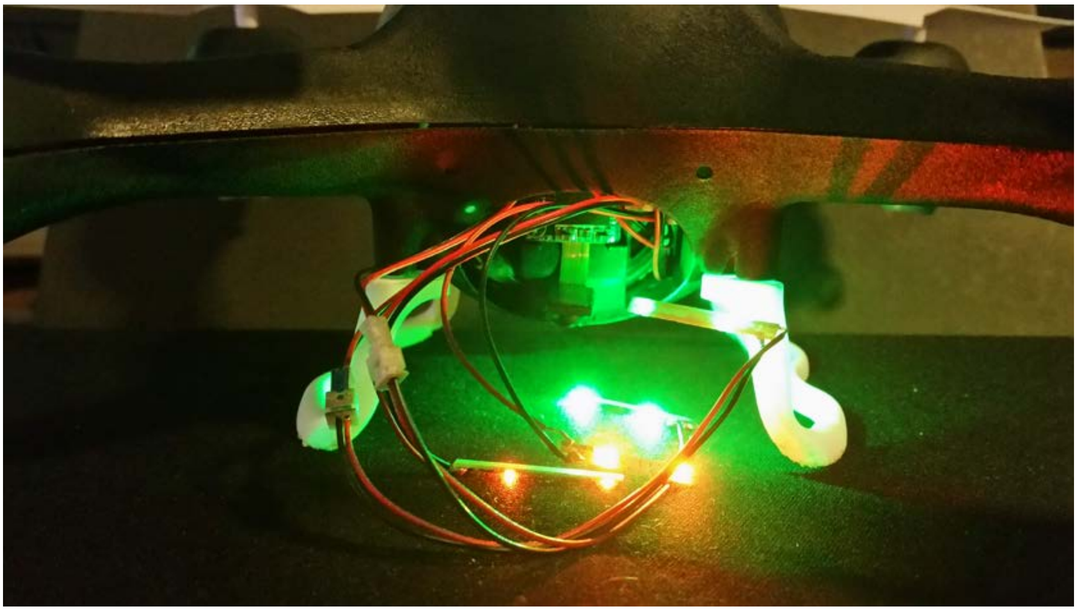

Figure 8-3 – light mode activated!

The literature review covering audio quality and has resulted in the speaker performing very well in the drone, with limited degradation to sound quality, even with the propellers turning at maximum speed.

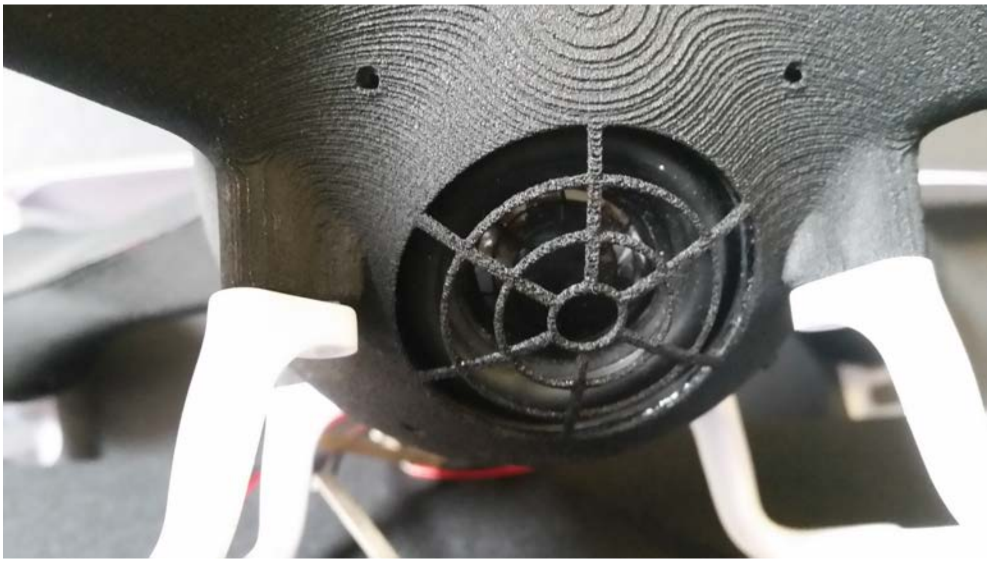

Figure 8-4 - Drone speaker and guard

As mentioned previously, the drone shells have suffered a minor stepping effect as seen in Figure 8-5. This has been caused in the regions highlighted due to the orientation of the part while it was being printed. For this AM process, it is unavoidable without actually increasing the x axis and y axis resolution.

Figure 8-5 - Stepping effect seen on the drone body

Despite the stepping effect, the drone has been designed very well. It can be seen in Figure 8-6 that the location pins and flats have achieved a good fit between the motor holder and drone arms. However, after the application of an acrylic spray coating, some of the location rims do not line up as well as prior to spraying due to minor deformation.

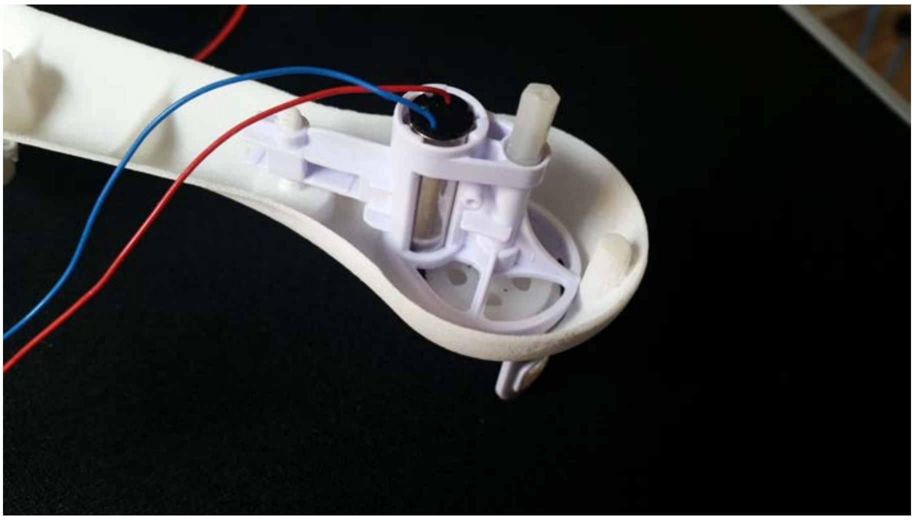

Figure 8-6 - Image showing the accurate fits achieved through extensive dimensioning of the original parts

As a first concept prototype, the drone has been successful in representing the redesigned concept's form and fit testing. All parts fit well within the shell and the PCB's do not interfere with each other. The drone does not fly however, due to the excess mass addition from the speakers and relatively dense printing material. The next iteration would require the investigation of higher power-weight ratio motors in order to lift the device and assess its flying capability.

9 Conclusion

The Syma X5C quadcopter was analysed using reverse engineering techniques and a redesign was proposed to improve certain functions with the inclusion of a wireless sound system. Analysis of the drone using non-contact and contact measurement methodology aided the production of a CFD model to assess the relative performance improvement between the two designs. However, the final assembly of the drone was above the weight specification, therefore experienced issues with lift.

The root cause of this effect was due to the relatively high material density of the additive processes compared to conventional materials used in injection moulding. With further development, correct material selection, and matching the power-weight ratio of the current drone, it is expected that this design would perform better in flight than the original design.

The spherical design of the drone not only benefitted the aerodynamic properties of the done but also the acoustic performance of the speaker. With the removal of the speaker system, the drone was able to fly and was less susceptible to crosswind interference. The barrel-roll feature was still possible with the new shell design.

Although the iris part was not manufactured in time, it was expected that it would improve the semantics of the drone as it used to be difficult to identify the orientation of the drone at height.

If this product were to be manufactured using additive processes, the wall thickness would need to be greatly reduced in order for the drone to fly. The current facilities available were not able to achieve a wall thickness of less than 0.7mm which may be achievable using conventional injection moulding techniques.

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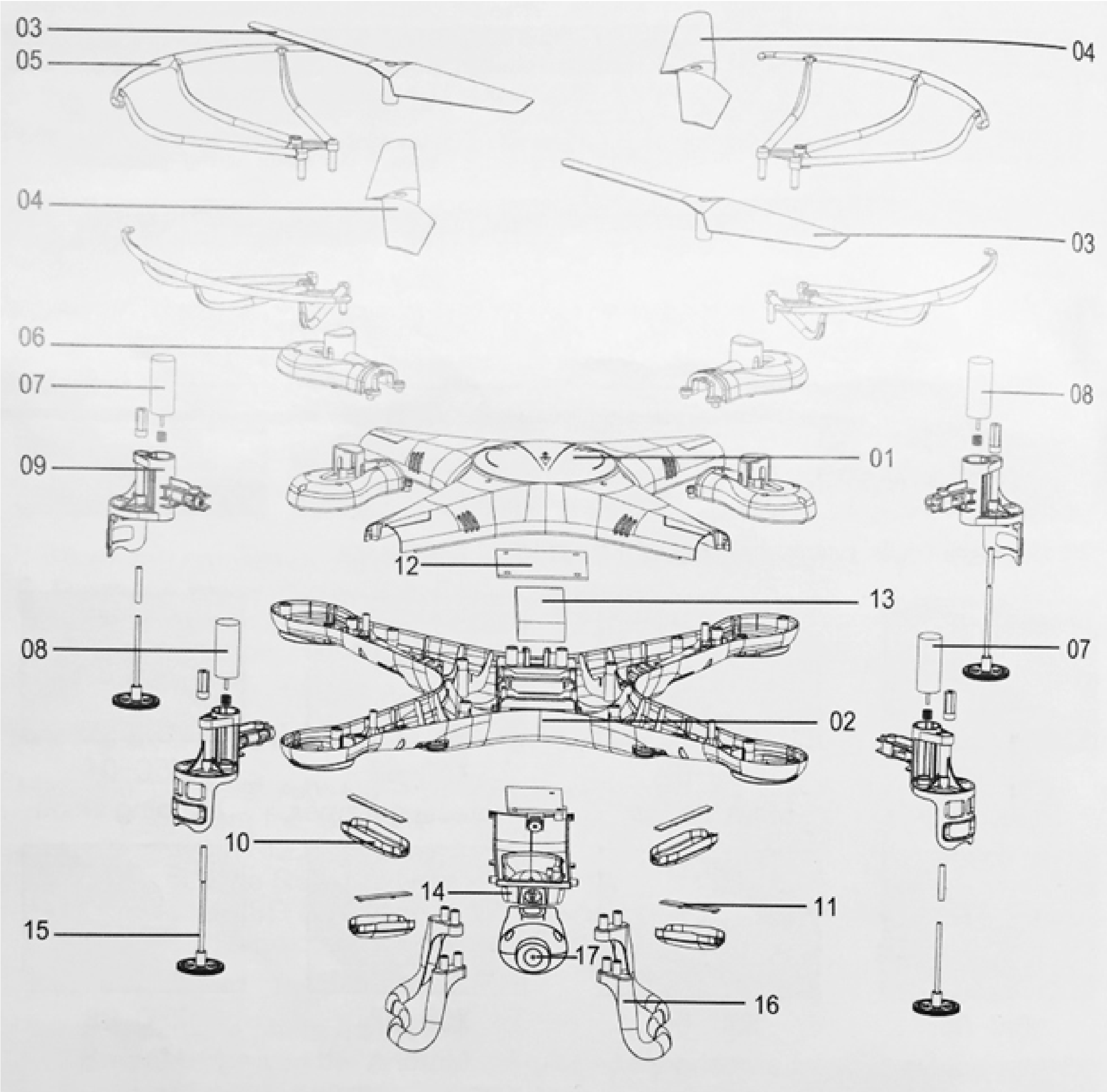
11 Appendix

11.1 Drone Schematic



11.2 Additional CAD images

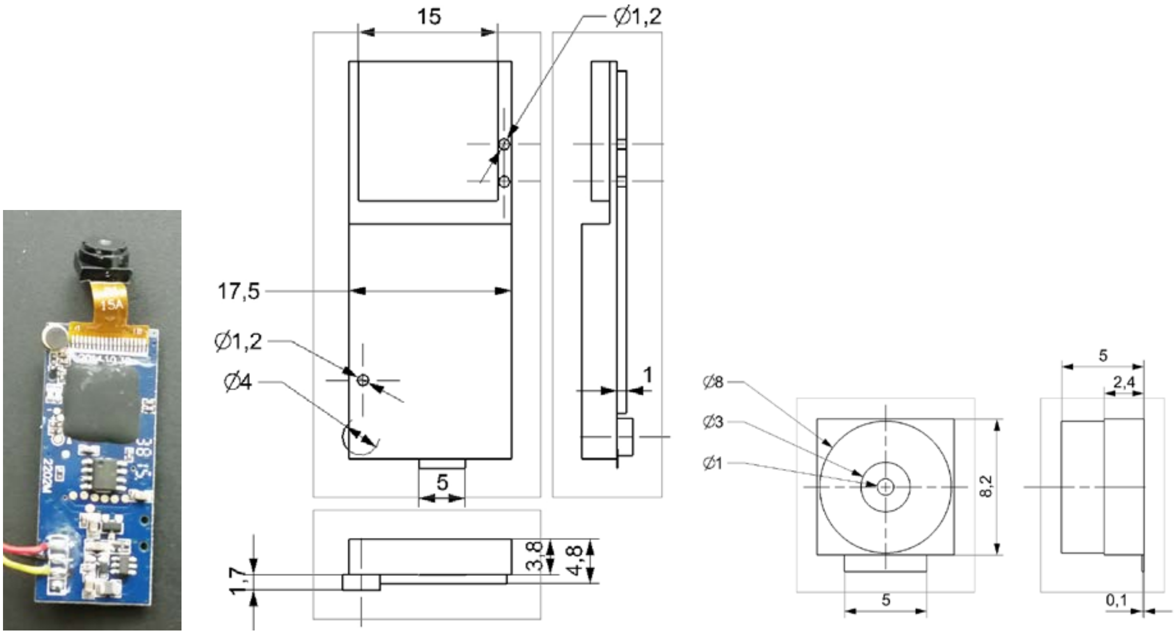


Figure 11-1 - Camera PCB and receiver

11.3 Mass and cost calculations

				Density of AM Materials (kg.m^-3)			
Parts	Mass (g)			PLA	ABS	Polyamide	Epoxy Based Photopolymer
Drone (Shell, Internals Feet and Guards)	92.99		kg.m^-3	1320	1070	1140	1200
Drone (Shell, Internals Feet and Guards) and Camera	97.06		g.cm^-3	1.32	1.07	1.14	1.2
Drone (Shell, Internals Feet and Guards), Camera and Speaker PCB	109.58			Ultimaker	Stratasys FDM	SLS	SLA
Drone (Shell, Internals Feet and Guards), Camera, Speaker PCB and Large Speaker	125.35			Cost per cm^3			
Drone (Shell, Internals Feet and Guards), Camera, Speaker PCB, Large Speaker and Small Speakers	133.50			£ 0.30	£ 1.25	£ 1.00	£ 2.00
Drone Internals	56.66			Ultimaker	Stratasys FDM	SLS	SLA
Shell, Feet and Guards	33.88			Max/Min Volume (cm^3)			
			Min	19.89	24.54	23.04	21.88
Drone Shell, Feet and Guards	36.33		Max	52.38	64.62	60.65	57.62
Feet ea. (2)	1.23			Ultimaker	Stratasys FDM	SLS	SLA
Camera	4.07			Cost Per Volume			
Speaker PCB	12.52		Min	£ 5.97	£ 30.68	£ 23.04	£ 43.77
Large Speaker	15.77		Max	£ 15.71	£ 80.77	£ 60.65	£ 115.23
Small Speakers ea. (2 Total)	4.08						
Maximum Additional Mass (+ Drone (Shell, Internals Feet and Guards))	60.00			57008			
Maximum Overall Weight (Lower Range)	117.73			Component Volumes (cm^3)	Component Masses (g)	Price (£)	
Maximum Overall Weight (Upper Range)	152.99		Shells (2)	50.288	57.32832	£ 50.29	
			Eye (1)	2.667	3.2004	£ 5.33	
Maximum Shell Weight (Lower Range) Assumption: Feet and Guards are used	26.26			Sum	60.52872	£ 55.62	
Maximum Shell Weight (Upper Range) Assumption: Feet and Guards are used	69.14						
			+ Feet		2.45		
			+ Internals		84.95		
			+ Guards				
					147.93	0.8	147.93
						0.7	143.13