Encapsulation of electronic hardware into FDM manufactured thermoplastic drone structures

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

Encapsulation of Electronic Hardware into FDM

Manufactured Thermoplastic Drone Structures

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Encapsulation of Electronic Hardware into FDM Manufactured Thermoplastic Drone Structures

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Abstract

FDM (Fused Deposition Modeling) additive manufacturing is allowing manufacturers to consolidate multiple complex assemblies into single printed parts, with minimal reduction in geometric complexity. This has the potential to reduce both manufacturing and assembly steps. This reduction in production stages can result in cost savings, reduction in assembly line components and also in fewer technical staff required for manufacturing operations. This thesis will build upon these ideas by adding electronic components into the 3D printing stage and will use a 3D printed quadcopter as an example. The aim is to demonstrate a proof-of-concept of functional electronic systems within a high temperature printing process, and to determine best practices for the embedding of hardware.

In order to reduce the number of fasteners in the printed drone, snap-fit clips were printed in-situ as part of the drone airframe. This thesis will examine some of the limitations involved when printing snap-fit clips of small scale, and provides a graph showing a zone of manufacturability, based on printer extrusion width dimensions for a given strain requirement. It is demonstrated that a clip must be a minimum of 0.8128 mm thick in order to be manufactured by 3D printing in accordance with the literature guidelines for snap-fit clips.

Additionally, it is shown that when a print job is paused, cooled and restarted in order to embed separate hardware items, the bond layer at the pause is weakened. This weakening effect results from the thermal history and this thesis will investigate and quantify the effects of cooling on the bond strength. In summary, the loss of bond strength cannot be recovered by reheating the part, and the loss of strength can be minimised by a combination of the highest print chamber setting (170°C), a minimal reheat time (2 minutes 5 seconds) and a cooling temperature of 80°C.

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1. Introduction

1.1 Background

1.1.1 Drone Market

UAVs (hereafter referred to as “drones”) have become big business in the last 5 years, with many consumer level companies such as DJI Innovations (China), Parrot (France), Hubsan (China) and GoPro (USA) all vying for a share of a largely untapped market which is currently estimated to be worth \$127 billion USD according to a 2016 market report by PwC. (PricewaterhouseCoopers, 2016).

In 2016 drones made their first appearance on the Gartner’s Hype Cycle for Emerging Technologies (figure 1.1), confirming that drones are very much an emerging technology that should be monitored by those who wish to capitalize on the technology. The hype cycle chart shows that drones are still in the innovation trigger phase, with an estimated 5-10 years before mainstream adoption of the technology takes place (Gartner, 2016).

Figure 1.1 Gartner’s hype cycle for emerging technologies 2016 (Gartner, 2016)

Drones come in a variety of sizes, ranging from small handheld quadcopter toys weighing just a few grams, to industrial octocopters and fixed wing aircraft used for precision agriculture (some weighing up to 20kg). At the pinnacle of drone technology lays the military grade drones such as the fixed wing MQ-1 Predator, which weighs in at 1020kg (takeoff weight).

1.1.2 Additive Manufacturing Market

According to Wohlers Report for 2016, the value of the existing 3D printing industry for 2015 was estimated to be \$5.1 billion USD and has shown a CAGR of 26.2% over 27 years (McCue, 2016). These figures include consumer grade desktop 3D printer, industrial 3D printers and associated services in the industry. According to a 2016 report on the AM market by PricewaterhouseCoopers, out of the manufacturing companies surveyed, 42% believed in 2015 that within 3-5 years, AM will be used primarily for the production of end-use components. That was an increase from 38% in the year 2014. As of 2015, 6.6% of the polled companies are using AM for end use products compared to 0.9% from the year 2014 (PwC, Manufacturing Institute, 2016). This data suggests that although AM is still primarily used for prototyping, more companies are adopting the technology for end-use products and there is a growing belief that more companies will adopt AM for end-use/mass production in the near future.

The 2015 Gartner Hype Cycle for 3D Printing (figure 1.2) shows a similar outlook. Use of AM in supply chain is predicted to reach the plateau of productivity in 5 to 10 years, and the same timeframe can be expected for use of 3D printing in manufacturing operations (Gartner, 2015).

At time of publication, the hype cycle suggested that the main area of productivity would be focused on prototyping, which is confirmed by the companies surveyed in the PwC report of the same year.

Figure 1.2 Gartner's Hype Cycle for 3D Printing 2015 (Gartner, 2015)

1.1.3 Additive Manufacturing for Drones

Commercial drones are generally manufactured using carbon fibre or moulded thermoplastics. At the higher end of drone manufacture, such as military applications, drones are manufactured from plastics, carbon fibre and also from metals such as aluminium and titanium. Given the thrust capabilities of small drone motors, using metals for small drones is out of the question. This leaves composites and plastics as the materials of choice for small drone manufacture.

There are several examples of drones that have been manufactured with AM processes, and the key benefits so far revolve around reduced development time and reduced cost. This reduction in development time is largely driven by the ability to produce parts in-house, which saves on delivery time, allows a faster design iteration cycle and a reduction in tooling. In this section, it is explained why FDM is the preferred manufacturing method compared to traditional and other additive manufacturing systems. For mass production of plastic parts, injection moulding is ideal for drone manufacture. The process is suited for a

wide range of plastics, and can produce parts with a high-quality finish suited to consumer grade parts, where a high standard of aesthetics is desirable. However, there is a high capital cost involved and it is not economical for small production runs or prototypes. A cost comparison will be conducted later in this thesis to highlight this fact, so the point will not be belaboured further in this introduction.

1.1.3.1 Carbon Fibre

Although carbon fibre is valued for its high strength and low weight, it is costly to manufacture due to tooling requirements for mass production. In large scale, it is possible to manufacture simple geometries such as tubes, plates and curved panels, as the moulds are reusable, but more exotic geometries tend to be manufactured on shorter production runs. In addition to the cost and difficulty in working with CF, this type of composite has other issues, namely its tendency to suppress radio frequency signals. Radio signal suppression is largely dependent on the orientation of the fibres, the joints in the structure and the frequency of the signal (Mehdipour, 2011). Due to the dependency of manual work involved in carbon fibre manufacture, there are variations in the final product which may produce unwanted or unpredictable RF shielding effects. At present, there are companies manufacturing additive manufacturing systems capable of single fibre deposition (such as the MarkTwo printer from Markforged) which can improve quality and repeatability of carbon fibre manufacturer, but due to the lack of soluble support material available to this system, printing with carbon fibre still lacks the ability to print structures as complex as those enabled by other common additive manufacturing processes such as extrusion-based FDM or SLA (Molitch-Hou, 2016).

1.1.3.2 Stereolithographic Apparatus (SLA)

SLA is a *vat photopolymerisation* process, and is known for being able to produce complex parts as well as smooth surface finishes (Chua & Leong, 2015). It does not have

the pronounced stepping effect that is seen on FDM manufactured parts. Conversely, parts manufactured with SLA are not as strong as FDM or carbon fibre parts, so they are generally used as highly aesthetic prototypes. In addition, there is an extra cost penalty involved with SLA processes. As it is a vat polymerisation process, there is a lot of wastage involved, and SLA photopolymer fluids are expensive.

Embedding electronics in SLA parts is problematic as well. Firstly, there is the need to submerge the electronic hardware in the fluid, and secondly, as the embedding process requires some manual installation and orientation, it can become a messy and cumbersome process. In addition, photopolymers can cure gradually with exposure to room-level lighting, so this is a consideration which must be made when pausing the machine for the embedding phase.

1.1.3.3 Fused Deposition Modeling

Fused Deposition Modeling (FDM) is a type of *material extrusion* process (ASTM International, 2015). The name “FDM” specifically applies to Stratasys’ proprietary material extrusion additive manufacturing machines, although it is used more generally to describe similar heated thermoplastic extrusion systems from other vendors. For the purpose of this thesis the term “FDM” will be used when describing this type of plastic extrusion process. FDM offers higher strength, than SLA and due to the nature of the FDM process; it is easier to work with. As this project requires the embedding of complex electronic subsystems, it is preferable to utilize FDM, as it is a dry process, which prevents potential damage of electronics as well as making a cleaner work environment.

ULTEM 9085 is a lightweight, high strength aerospace industry rated polyetherimide-based amorphous polymer, and has been used in many aerospace applications already. As ULTEM 9085 has been flight-proven and has various certifications for toxicity, flammability, smoke, as well as other desirable properties such as low outgassing, there is

not only a mechanical case for using this material for drone manufacture, but a regulatory case as well- if embedded electronics are to be used in aerospace applications in future, it is preferable to use materials and processes that have already passed the required regulations for use in aviation or spaceflight, rather than certifying an untested material, which can be time consuming and costly.

Table 1 ULTEM 9085 aviation FST ratings (Stratasys, 2016)

Property	Test Method	Value
General		
Flame Classification	UL94 V-0	(1.5 mm, 3 mm)
Oxygen Index	ASTM D2863	0.49
OSU Total Heat Release (2 min test, .060" thick)	FAR 25.853	16 kW min/m ²
UL File Number		E345258
Outgassing		
Total Mass Loss (TML)	ASTM E595	0.41% (1.00% maximum)
Collected Volatile Condensable Material (CVCN)	ASTM E595	-0.1% (0.10% maximum)
Water Vapor Recovered (WVR)	ASTM E595	-0.37% (report)
Burn Testing		
Horizontal Burn (15 sec)	14 CFR/FAR 25.853	Passed (0.060" thick)
Vertical Burn (60 sec)	14 CFR/FAR 25.853	Passed (0.060" thick)
Vertical Burn (12 sec)	14 CFR/FAR 25.853	Passed (0.060" thick)
45° Ignition	14 CFR/FAR 25.853	Passed (0.060" thick)
Heat Release	14 CFR/FAR 25.853	Passed (0.060" thick)
NBS Smoke Density (flaming)	ASTM F814/E662	Passed (0.060" thick)
NBS Smoke Density (non-flaming)	ASTM F814/E662	Passed (0.060" thick)

1.1.4 Summary

From examining the market data and the predictions from the hype cycles, it can be shown that both the drone industry and the 3D printing industry are still in their innovation phases yet are still enjoying significant growth, with predictions for widespread use of drones and 3D printing in end-use manufacturing both coinciding within 5-10 years.

There have already been demonstrations of use of 3D printing for manufacturing prototype drones, and if the hype and past history is to be believed, then it is a fair assumption to

state that there will be more of an overlap of drones and end-use AM in future. Or to put it another way, if companies can save money by using 3D printing to reduce the steps in manufacture to build drones more effectively and on demand, then there is likely to be a rise in commercial and industrial grade 3D printed drones in the not-too-distant future.

FDM has been selected for ease of installation of hardware, and for the reduced risk of damage to components which may result from submersion in photopolymer fluids. The thermoplastic ULTEM 9085 has been selected for its superior strength to weight ratio, as well as its pre-existing aviation certifications which make it a preferred material should embedded additive manufactured be used for aviation in the future.

This thesis will focus on additive manufacture of end-use drones and the lessons learned from embedding hardware and will recommend guidelines for using this method of combined manufacture and assembly.

1.2 Significance and Motivation

Additive manufacturing with FDM allows the opportunity to embed electronics in the printing phase, which in larger applications could offer mass savings via reducing structural components such as mounting brackets, electrical covers or even aerodynamic surfaces. In addition to the reduction in component inventory, encasing electronics with this method offers the benefit of protection from external environments such as dust, moisture, fluids and potentially even the vacuum of space.

At present, there are some companies such as Voxel8 who are moving towards combined 3D printer/PCB manufacture by printing conductive tracks within FDM manufactured parts. This is one possible solution to the issue of combining manufacturing steps. Another solution, as proposed in this thesis, is to combine pick and place processes with FDM 3D printing. This thesis will not use automated assembly however, and will focus on determining best practices based on manual insertion during print.

1.3 Objectives

The main objectives of this study are as follows:

- Conceptualize and design a 3D printable small-size drone for manufacture in one integrated manufacturing stage.
- Identify challenges in embedding hardware during high temperature printing.
- Determine experimentally the optimal printer parameters for embedding hardware with minimal loss of material strength at the bond layer.
- Provide best practices and solutions for embedding hardware in 3D printing process.

1.4 Scope of Work

This study is to be started with a literature review of the current state of the art regarding medium sized commercial quadcopters, 3D printing and the embedding of electronic hardware into 3D printed structures.

It is to be followed with the design and manufacture of an FDM 3D printed quadcopter drone using the aerospace-grade ULTEM 9085 thermoplastic, complete with embedded electronics hardware. A qualitative assessment of the flight characteristics of the drone will be performed.

The study will look at some of the issues associated with embedding hardware in a high temperature printing environment, based on the manufacture of the 3D printed drone. For the purpose of this thesis, the term “high temperature” refers to the relatively high temperatures used in the Fortus 450mc printing chamber when printing with the ULTEM 9085 thermoplastic. For printing with ULTEM 9085, constant print chamber temperatures

of 160°C or higher are required in order to reduce the warping of the part, which is caused by uneven cooling. This is compared to the lower chamber temperatures required for other common FDM printed plastics such as ABS Plus (acrylonitrile butadiene styrene), which requires a chamber temperature of 75°C, or PLA (polylactic acid) which can be printed with just a heated print bed (no heated chamber required).

One such issue when printing at these high temperatures is the presence of a weakened bond layer, which results from the cooling of the printed part when the printer is opened for embedding the hardware. A 2³ full factorial experiment has been designed and will utilize tensile specimens which have been subjected to similar conditions experienced during the drone manufacture.

The results of the experiment are to be analysed to determine the best combination of factors resulting in the highest strength samples when performing such a process. These results will form the basis of a set of best practices guidelines, designed for embedding hardware in an FDM process.

In addition, there will be a section on design of snap-fit clip fasteners, and it will be demonstrated by hand calculation and finite element analysis plots that there are limitations to using the classic clip design methods with regards to dimensional capabilities of 3D printers. Recommendations for the optimal design method will be made.

1.5 Organization

Chapter 1

Introduction

This chapter contains an overview of the study and includes the background, objectives and scope of the thesis.

Chapter 2

Literature Review

This chapter provides an in-depth literature review on commercial drone manufacturing, the current state of embedded electronics in 3D printed structures, DFA methods, FDM methods and previous research on FDM bond strength.

Chapter 3

Design and Manufacture of Drone

This chapter describes the design and manufacture of the 3D printed drone and contains technical illustrations of the manufacturing steps. In addition, the flight performance of the drone is qualitatively assessed.

Chapter 4

Bond Strength Experiment

This chapter details the factorial experiment design, the procedure and the results analysis.

Chapter 5

Best Practices for Embedding Hardware

This chapter uses the results from the bond strength experiment as a baseline for best practices when embedding hardware in 3D printed structures build with the FDM method.

Chapter 6

Conclusions and Recommendations for Future Work

This chapter contains a summary of the thesis, as well as future recommendations for testing 3D printed tensile specimens.

2. Literature Review

2.1 Commercial Drone Manufacturing

DJI Innovations are the market leader for commercial multicopters, accounting for 70% of global consumer/prosumer drone sales in 2015. DJI are not public with their sales figures, but it has been reported in media sources that 400,000 units were sold in 2014 (Ryan, 2015). Most of those sales consisted of their popular *Phantom* model.

Commercial quadcopters in their most basic form consist of the following components.

- Airframe
- 4x Motors
- 4x ESC (electronic speed controllers)
- 4x propellers
- FC (flight controller)
- Lithium Polymer battery pack
- Radio Receiver
- Antenna
- Wiring and connectors

Figure 2.1 DJI Phantom 3 (DJI, 2016)

In addition to the basic components, a controller is also required. This can be in the form of a radio transmitter, a smartphone/tablet or a dedicated ground station computer. For the purpose of this thesis, the manufacture of the controller will not be studied.

Due to the complexity of the assembly work resulting from the geometry of the components, drones such as the DJI Phantom (figure 2.1) are largely assembled by hand on a production line.

The scale of assembly and manufacture differs from company to company with some choosing to procure flight hardware from a separate company to be assembled in a dedicated assembly factory, while others such as 3D Robotics (US) elect to build most of their hardware (PCBs, wiring harnesses) in-house, with only the chips being manufactured off-site (Ryan, 2015).

The decision to use automated or manual assembly processes for manufacturing is not arbitrary. Each strategy can be determined based on the fixed and variable costs along with the desired scale of the production run.

The graph (figure 2.2) shows that for a small number of units manual assembly yields the lowest cost per unit (due to the capital (fixed cost) required for the purchase of machinery, and automated assembly yields a higher cost per unit. At a certain point (N^*) this trend

Figure 2.2 Manufacturing costs (Boothroyd, Dewhurst, & Knight, 2011)

switches and it becomes more cost effective to use automated manufacture for larger production runs.

The choice to pursue an automated or manual assembly process is decided on the following factors:

- Cost of equipment
- Payback period
- Number of parts in assembly
- Number of product styles of assembled product
- Expected production run size

In general, drone manufacturers use manual assembly for the airframe and larger components, and for components with difficult handling ratings such as wiring harnesses and other non-symmetrical parts as recommended by traditional DFA methodologies such as the Boothroyd-Dewhurst method (Boothroyd, Dewhurst, & Knight, 2011).

2.2 Embedding Electronics in Additive Manufactured Structures

2.2.1 Overview

Embedding electronics in AM structures is a relatively new field of research and can generally be divided into two schools of thought.

The first involves the direct printing of components and this can be further subdivided into two areas: those which utilize a single conductor, for producing simple components such as conductive tracks, basic switches and resistors, and those which use multiple materials for producing more complicated components such as transistors, LEDs or batteries (Saengchairat, Chua, & Tran, 2016).

The second approach involves the embedding of complete, prefabricated, components. This allows more complex subsystems to be embedded, and this thesis project falls into this category.

Figure 2.3 Micro strip Transmission Line (Dumene & Kennedy, 2015)

2.2.2 Embedding- PolyJet

PolyJet is the name of Stratasys' proprietary *material jetting* process (ASTM International, 2015), and is similar to ink jet in a traditional paper printer, but uses photopolymer ink which is cured after each layer by use of a strong UV lamp. There have been experiments with embedding basic electronic components (figure 2.3) in PolyJet and work is on-going in this field, so there is potential for use of this method for embedding more complex electronics (Dumene & Kennedy, 2015). The main benefit of using PolyJet is the wide range of materials on offer, ranging from thermoplastic-like engineering plastics to elastomer-like materials. The strongest material available to PolyJet users is currently the RDG525 plastic, which has a tensile strength in the region of 70-80 MPa and a density of 1.17-1.18 g/cm³ (Stratasys, 2015). The process of embedding complex subsystems had not been attempted at time of writing, but given the range of materials available and the high strength, low density of these materials, PolyJet is potentially a viable candidate for the manufacture of drones with embedded electronics. As with the SLA method, caution does need to be exercised when embedding electronics this way, due to the likelihood of fluids coming into contact with conductive components.

2.2.3 Embedding- FDM

There have been several projects published that have involved the embedding of electronic components during the material extrusion/FDM process. Most notably was the Voxel8 drone project, which utilises the Voxel8 3D printer which features both plastic extrusion capability and also the capacity to extrude a conductive silver ink (MacDonald & Wicker, 2016).

In the Voxel8 drone (figure 2.4), the PLA plastic was deposited layer by layer, to form the airframe. At a specified point, the plastic extrusion was ceased and the deposition of the conductive tracks began. Similar to the drone in this thesis, the prefabricated electronic systems were embedded (by hand) into the drone before the printer was resumed to encapsulate the electronics.

Figure 2.4 X-Ray of Voxel8 drone and conductive tracks (MacDonald & Wicker, 2016)

Researchers at University of Hamburg have taken this one step further. In the Hamburg project, not only are the plastic and conductive tracks printed (figure 2.5), but also a computer-vision assisted pick-and-place mechanism has been installed as well (Wasserfall, 2015). The project utilizes a CNC milling machine as the base platform, and onto this, a

vacuum assisted pick-and-place system, a screw-driven syringe for extruding conductive paste and the plastic filament extruder are installed. So far, simple systems such as USB sticks have been fully fabricated with this method. Both the Voxel8 system and the Hamburg system are designed to operate in a low temperature environment, without a heated chamber.

Figure 2.5 Extruded substrate and tracks (Wasserfall, 2015)

2.2.4 Direct Printing- Multimaterial Nanocrystal Colloids

This method is a multi-stage process currently under research at University of Pennsylvania. The team have used a combination of lithography and spin coating on multiple materials for the fabrication of FETs (Field Effect Transistors) by layering the different materials onto a flexible Kapton substrate. The FETs in the project required four basic components, being an insulator (aluminium oxide), a conductor (silver), a semiconductor (cadmium selenide) and a dopant/conductor (indium and silver). Nanocrystals of each of those substances were added to liquids for layer-wise application. Although it is not technically at the point where it can be referred to as 3D Printing, it can be classed as an additive manufacturing process, and the research team are stating that due

to the colloidal nature of traditional conductive inks, this method can in principle be adapted into a 3D printing process (inkjet or extrusion).

Figure 2.6 highlights the steps involved in the process, and the process is described as follows:

“(i) Photolithographic patterning and Ag NC spin-coating and ligand exchange; (ii) resist lift-off to define Ag NC gate electrodes; (iii) layer-by-layer spin coating of PDDA and PSS and then alternately Al_2O_3 NCs and PSS to grow the gate insulator layer; (iv) spin coating of SCN-exchanged CdSe NCs to form the semiconductor channel layer; (v) photolithographic patterning and Ag NC/In NC spin coating and ligand exchange; and (vi) resist lift-off to yield patterned electrodes. Devices are thermally annealed at 250°C for 10 min in the nitrogen glovebox”. (Choi & Wang, 2016)

Figure 2.6 Nanocrystal transistor process (Choi & Wang, 2016)

2.3 Methods for DFA

DFA / DFM (Design for Assembly / Design for Manufacturing) are design philosophies and strategies intended to reduce cost of manufacture by applying design rules in order to reduce manufacturing and assembly steps.

DFM focuses on the manufacture of individual components, such as parts that can be machined or injection moulded, and offers guidelines for cost-efficient manufacture by reducing unnecessary manufacturing steps, tool changes and flaws which may require rework, by addressing these concerns in the design phase where it is still easy to address them. DFA is concerned with the feeding, handling and difficulty of installation of components into a larger assembly, and can cover automatic and manual processes on a production line. The key aspect of DFA is to reduce part count, and hence reduce assembly time. A reduction in assembly time will therefore allow greater number of assemblies to be produced for the same period of time, and will increase profits/reduce cost.

There are several different DFA/DFM processes, and the four most commonly used are BDM (Boothroyd-Dewhurst Method), the Hitachi Assembly Evaluation Method, the Lucas DFA Method and the Fujitsu Productivity Evaluation System. The Fujitsu system is only suitable for manual bench-work, so it is not covered in this review. A brief description of the other methods is as follows:

2.3.1 Hitachi Assembly Evaluation Method (AEM)

Parts are assigned an ease-of-assembly evaluation score (E_i) based on the simplest installation (fitting) motion, which is a simple downward motion with no interference or fastening required. The simplest parts are assigned an E_i score of 100. If there are any deviations from this ideal simple installation (such as securing, fastening etc.) then penalties are applied to the E_i score for each part and the score drops from 100. Once all the parts have been assessed and tabulated, they are multiplied with N (the total number of parts) to provide a total E-score for the assembly (written as “E”). If the total score is high, then this is the optimum design in terms of efficiency. If the score is lowered due to penalties, then it is considered a poor design in terms of assembly. The scores are

transposed into costs at the end of the analysis, making this a cost-based system. The AEM system does not distinguish between robotic, manual and automated assembly, nor does it take into account aspects such as gripping and easy of feeding. (Eastman, 1996)

2.3.2 The Lucas DFA Method

Similar to the Hitachi method, the Lucas method takes an ideal process, assigns a score and then penalises that score for any extra difficulty. The main difference is, that while the Hitachi method only examines the installation phase, the Lucas method breaks down the assembly process into three sequential stages. These three stages are *functional efficiency*, *feeding*, and *fitting*.

The functional efficiency (E_d) examines parts and designates them as either an A-part (essential) or a B-part (not essential) and the efficiency of the design is calculated by examining how many superfluous B-parts there are in relation to the total number of parts.

$$E_d = A/(A+B) \times 100\%$$

This is similar to the design efficiency calculation in BDM.

The feeding analysis uses geometric and other factors to determine a feeding index from a table. Every part is examined and designated with an index, with an index of 1.5 being the maximum allowed before a part should be redesigned or replaced. Once the part feeding index has been assigned, the total index of all components in the assembly is calculated and a feeding ratio can be determined:

$$\text{Feeding Ratio} = (\text{Total Feeding Index}) / (\text{Number of Essential Components})$$

A feeding ration of 2.5 is ideal, and any significant deviation over that value will call for redesign.

The procedure for calculating the fitting index is similar. Parts are assigned values from a table, based on ease of installation, with 1.5 being the target for each item, and 2.5 being the maximum target for the whole assembly fitting ratio.

$$\text{Fitting Ratio} = (\text{Total Fitting Index}) / (\text{Number of Essential Components})$$

(Chan & Salustri, 2005)

Unlike AEM and BDM, Lucas is not cost-based. The final outcome of the Lucas analysis is in the form of a percentage, or ratio, based on previous designs. Due to the absence of cost considerations in this type of analysis, there is no consideration for the manufacturing cost while making design changes, which if left unchecked, can lead to costly products. An additional disadvantage of this system is that the Lucas system does not differentiate between different types of automatic assembly, unlike BDM. (Eastman, 1996)

2.3.3 Boothroyd-Dewhurst Method

BDM operates on the premise that assembly and manufacturing time is the largest cost driver, and uses tables of geometric shapes (see figures 2.8 and 2.9) to determine the time taken to orient and insert a component into an assembly. The tables are based on historic, experimental data. Additionally, the BDM method examines the types of fastener required, and assigns time values for each different type of fastener.

Typically, an engineer using BDM will evaluate the total number of parts within an assembly, assign time values to each component based on *handling* and *insertion* time, and will insert the data into an *assembly matrix* (see figure 2.7). After some calculation, the total assembly time and the cost per assembly can be determined.

Additionally, by examining the individual components and by following a set of heuristic guidelines, it is possible to determine the so-called *minimum part count*. The

minimum part count can be used to measure the design efficiency of an assembly, and can be used for reducing the number of components in an assembly, and hence reducing the cost of the product.

In summary, the steps required for Boothroyd-Dewhurst DFA method are as follows:

- 1) Design product
- 2) Create assembly matrix based on
 - Handling table (size, weight, orientation)
 - Insertion table (part alignment, type of fastener)
- 3) Determine Theoretical Assembly Time (TAT)
- 4) Calculate Design Efficiency Index
- 5) Iterate and optimise assembly design

2.3.4 Key points

Both Hitachi and AEM are cost-based, so they are advantageous in the sense that it is easier to monitor costs in redesigns. The Lucas system is similar to BDM as it considers all aspects of the assembly line, and not only the installation phase as is the case with AEM.

BDM considers multiple types of robotic insertion systems compared to the AEM and Lucas methods.

To get a more complete cost-based overview of a traditional assembly line, it can be argued that BDM is the more complete system as it covers feeding, transfer and installation, manual work and robotic work of several types.

Although AEM does have disadvantages regarding the lack of distinction between automated, robotic and manual installation which make it flawed for evaluating mixed assembly lines, it does have a baseline that is well-suited for manual part installation inside

a 3D printer. When installing hardware in a printed item, one must be aware of the risks of injury from heat, from dislocating the part from the bed, and also one must be aware that the part is undergoing thermal contraction if the printer door is open. To this end, the AEM system does provide a reasonable target: to opt for parts that can be installed with a downward motion, with little force or fastening required.

In general the aim of DFMA is to reduce time taken for manufacture and assembly. The cost of the end product is a function of the time taken to perform tasks. The time taken to perform these tasks can be reduced by adhering to the following general DFMA guidelines which are an amalgamation of methods proposed by Boothroyd and Dewhurst, Hitachi Ltd. and Lucas Industries Plc (Leaney & Wittenberg, 1992).

1. Reduce the part count and types
2. Modularise the design
3. Strive to eliminate adjustments
4. Design parts for ease of feeding or handling
5. Design parts to be self-aligning and self-locating
6. Ensure adequate access and unrestricted vision
7. Design parts so they cannot be installed incorrectly
8. Use efficient fastening or fixing techniques
9. Minimise handling and reorientation
10. Utilise gravity
11. Maximise part symmetry.

(Leaney & Wittenberg, 1992)

2.4 3D Printing of Snap-fit Clips

2.4.1 Overview

Plastic snap fit clips are one of the cheapest methods of fastening components together (BASF Corporation, 2007). Additionally, they can help to reduce part inventory because they can be incorporated into the manufacturing process for the parts to be mated in question. For example, a 2 part fuse-box cover may normally require additional 4 (or more) items of hardware fasteners such as bolts in order to mate the cover of the box to the base.

Not only does the addition of extra items increase part inventory, but it can add to the weight of the product, which is undesirable in aerospace applications. In addition, the usage of extra hardware fasteners often requires extra tools such as sockets, spanners or screwdrivers in order to assemble and disassemble the product for inspection or maintenance. This can contradict Design for Assembly and Design for Maintenance guidelines (Boothroyd, Dewhurst, & Knight, 2011). For these reasons, in certain applications it is desirable to use lightweight and durable thermoplastic clips, which are designed into the product, and can enable repeated rapid assembly and disassembly.

Figure 2.7 Clip geometry and mould complexity (BASF Corporation, 2007).

Traditionally these clips are manufactured using an injection moulding process and depending on the type and geometry of the clip, can add complexity and cost to the manufacturing process. As can be seen in figure 2.7, an injection moulded clip can require the addition of mould slides which add cost to the mould system design. Even the slot design on the second example requires extra mould machining which adds cost and

complexity (Boothroyd, Dewhurst, & Knight, 2011). However, in a part manufactured with FDM, this additional geometric complexity incurs negligible or zero extra cost penalty as there is no need for additional tooling. Each of the three examples depicted in figure 2.7 will cost approximately the same as each other when 3D printed. However, due to the anisotropic nature of FDM parts, they do incur penalties in terms of mechanical strength, depending on the print orientation of the part (figure 2.8).

Figure 2.8 *Print orientation naming conventions*

As of July 2017, there are no FDM machines capable of switching print orientation mid-print, so consequently consideration must be made to ensure that the clip and the main part body are printed in an orientation that offers maximum strength to the clip without compromising the strength of features on the main body. The main body and the clip must be printed in the same orientation, ensuring that the filament tracks run longitudinally along the length of the clip.

Figure 2.9 *Anisotropic strength according to print orientation*

Previous research (Bagsik, 2011) has shown that of tensile test coupons printed in three different orientations, those printed in the X-direction display the highest tensile strength and greatest elongation before the specimen breaks (figure 2.10). Conversely, those items printed in the Z-Direction show lowest tensile strength loading and elongation before the part breaks. When an item is printed in the X or Y direction, the maximum strength the specimen can take before breaking is a function of the material property, and the tensile forces run parallel (or at angles) to the filament tracks. When the specimen fails, it actually breaks.

Figure 2.10 Stress Strain curve for different build orientations (Bagsik, 2011)

When the specimen is printed in the Z-direction and subjected to loading, the tension is experienced perpendicular to the filament track and to the layers, thus the failure mode is not so much a break of the filaments, as is the case with X and Y specimens, but is a failure of the bonding in between layers (figure 2.9). This implies that the bond strength is not as strong as the original filament material (Bagsik, 2011).

Conclusively, the strongest clips manufactured with FDM process will be manufactured in the X-direction.

2.4.2 Clips as Beams

In its most basic form, a cantilever clip can be thought of as a beam undergoing deflection and to this end a basic clip can be designed using classical beam theory (Euler-Bernoulli Beam Theorem).

There are 2 main components to consider in this basic clip design:

- 1) The strain and permissible deflection force of the clip arm itself
- 2) The mating force required to for the arm to overcome friction and mate into the receptacle

Figure 2.11 Strain shown in polarized light photograph (Bayer Material Science, 2010)

Additionally, the clip arm should ideally be tapered from the root to the hook/tip in order to allow even distribution of strain/stress (figure 2.11). For this reason, there are different governing calculations dependent on the cross section and taper of the arm (Bayer Material Science, 2010) (BASF Corporation, 2007).

Table 2 Snap fit hook geometry (Bayer Material Science, 2010)

Permissible Deflection		$y = 0.67 * \frac{\varepsilon * l^2}{h}$
	$y = 1.09 * \frac{\varepsilon * l^2}{h}$
	Deflection Force	$P = \frac{bh^2}{6} * \frac{E_s \varepsilon}{l}$

2.5 FDM Process for Thermoplastics

2.5.1 Printing Process

FDM (Fused Deposition Modeling) is an Additive Manufacturing (AM) process used for rapid manufacturing of both prototypes and end-use parts. Generally AM processes fall into one of three main categories based on their feedstock. These are solid, liquid and power-based systems. FDM falls into the “solid” based category, as its material input is in the form of thermoplastic filaments. (Chua & Leong, 2015)

Like most AM processes, the typical FDM process begins with a CAD (Computer Aided Design) model which is then converted into an STL (stereolithography) file. The design is typically achieved in the native design software’s format before being converted to STL. In the case of this project, all design work has been carried out within *Solidworks* CAD software, and has been converted to STL within the same software package.

Once a virtual model has been completed and converted to STL format, it can be exported into the 3D printing slicing software analysis and optimization for the actual print job. In this project, *Stratasys Insight v10.2* software was used for optimization prior to printing. Once within the software, the STL model is sliced along its horizontal planes into layers,

and toolpaths are generated for export into the 3D printer build software (in this case, the build software is *Stratasys Control Centre*).

These steps mentioned up until this point are common to most forms of additive manufacturing processes. In general, most begin with a CAD model, then conversion to STL, followed by a slicing process and a toolpath file generation. The FDM process branches off and becomes unique after this point.

Once the toolpath (.cmb file) is generated, it is sent into the Control Centre software for “packing”. If required, other jobs and toolpath files can be combined to allow multiple jobs to be printed during the same print session depending on the printer build plate area size. For the projects listed in this paper, the maximum build plate (and therefore the maximum part footprint) was 400mm x 400mm for the Fortus 450mc machine and 200mm x 200mm for the Stratasys Dimension Elite printer. (Stratasys, 2015).

After the various print jobs have been arranged in *Control Centre*, and the various parameters such as layer resolution and material density have been adjusted, the job is sent directly to the printer and the FDM process begins. Typically, FDM machines utilize 2 different types of feedstock. These are the main material, (referred to as the “model” material) and the support material. Model material comes in a variety of thermoplastics and for the drone project ULTEM 9085 material has been used.

Support material also comes in a variety of types ranging from soluble PLA materials to break away structures. Both model and support materials come in the form of spooled filaments encased inside a DRM protected cartridge, which is inserted into the printer before work begins.

Once the FDM process is initiated, the print chamber and extruder heads are heated up to the correct temperatures (depending on the feed material) and the material filaments are

automatically fed from the feedstock cartridges into the heated extruder head. (Chua & Leong, 2015)

The filament is metered through the extruder head and is heated to a semi-liquid state as it passes through the extruder's heating elements. The molten plastic is extruded onto the build plate according to the XY coordinate data specified in the toolpath- file. Once a layer is completed, the build plate is moved down by the depth of 1 layer in the z-axis to allow the next layer to begin. As the freshly extruded molten plastic hits the cooler layer beneath, it begins to solidify- and thus a solid part is formed over the duration of the layering cycle (Chua & Leong, 2015). The exact metering of the filament makes FDM an efficient use of materials compared to other plastic additive manufacturing processes, such as those using photopolymerization. In the case of such photopolymerization methods, there is significant waste due to partial curing caused by exposure to the light source as well as background lighting. As a result, the surplus photopolymeric resins cannot be reused after a print job is complete, if consistently predictable quality is required.

Table 3 Advantages and disadvantages of FDM

Advantages	Disadvantages
Fabrication of functional (end use) parts	Restricted accuracy
Minimal wastage (compared to photopolymer methods)	Slow process
Ease of support removal	Unpredictable shrinkage during cooling
Ease of material change	
Large build volume	

2.5.2 ULTEM 9085 Overview

ULTEM 9085 is a blended polyetherimide (PEI) thermoplastic, designed originally by GE Plastics, now owned by Sabic. It can be purchased in granular form for injection moulding and also as a spooled filament for 3D printing in the Stratasys Fortus 450mc and 900mc

printers. ULTEM 9085 is a high-end engineering thermoplastic, and is suitable for use functional prototype and end-user applications. What differentiates ULTEM 9085 from other thermoplastic filaments is its high performance across a number of mechanical properties, its FST ratings, and its existing certifications for aerospace applications (in particular its conformance to FAR 25.853). Additionally, its excellent thermal resistance and low outgassing properties make it ideal for use in spacecraft applications in vacuum. A selection of relevant material properties are shown in the table 2.3, and the full material data tables can be found in Appendix A.

Table 4 ULTEM 9085 material data summary (Stratasys, 2016)

Mechanical Property	Test Method	XZ Orientation	ZX Orientation
Tensile Strength, Yield	ASTM D638	47 MPa	33 MPa
Tensile Strength, Ultimate	ASTM D638	69 MPa	42 MPa
Tensile Modulus	ASTM D638	2,150 MPa	2,270 MPa
Flexural Strength	ASTM D790	112 MPa	68 MPa
Flexural Modulus	ASTM D790	2,300 MPa	2,050 MPa
Flexural Strain at Break	ASTM D790	No break	3.70%
Compressive Strength, Yield	ASTM D695	100 MPa	87 MPa
Compressive Strength, Ultimate	ASTM D695	181 MPa	90 MPa
Outgassing & Thermal Properties		<i>Not Dependent on Orientation</i>	
Total Mass Loss (TML)	ASTM E595	0.41% (1.00% maximum)	
Heat Deflection (HDT)	ASTM D648	153°C	
Glass Transition Temperature (Tg)	DSC (SSYS)	186°C	
Coefficient of Thermal Expansion	ASTM E831	65.27 $\mu\text{m}/(\text{m}\cdot^{\circ}\text{C})$	

2.6 Bond Strength in FDM Filaments

Parts manufactured with FDM processes suffer from anisotropic strength characteristics. They are stronger in X and Y axis, because the strength in those orientations is a result of the raw material properties. In the Z axis, however, the strength of the part is a result of the

inter-filament bonding strength, and the bonding strength is weaker than the strength of the raw material.

In simplified terms, it is comparable to a plank of wood, where the greatest tensile strength can be demonstrated where the forces run longitudinally allowing the force to be distributed along the fibre lengths, whereas the weakest tensile strength lies perpendicular to the direction of the fibres.

It has been demonstrated experimentally that the strength of the bond is related to the length of the bond (the neck) in between the filaments, and that the length of the bond is related to the thermal history of the filament (Bellehumeu, Li, Sun, & Gu, 2004).

This has also been observed during the drone project in this thesis (opening the printer and cooling the foundation part down before printing on top of it will have a negative effect the strength). This is investigated in detail in chapter 4.

Figure 2.12 The stages of sintering for polymers (Li, Sun, Bellehumeur, & Gu, 2002)

During a sintering process for polymers the following steps occur:

- 1) Contact between the filaments
- 2) Wetting due to surface tension
- 3) Creation of interface zone by diffusion
- 4) Randomization of polymer chains

The neck growth can be expressed as a dimensionless ratio of neck radius (y) with the filament radius (a), as indicated in Figure 2.12.

Prior research has shown that bond length and bond quality are both important and are distinct factors in determining the strength of the bond. Most of the bond neck growth occurs at highly elevated temperatures, and has been modelled numerically with a certain

degree of predictability, with the errors being attributed to thermal/mechanical creep. The creep occurs when the layers are extruded on top of one another at high temperature. The preceding layers are compressed by successive layers while they are still malleable, which adds to the neck (bond) length (Graybill, 2010).

Additionally, bond length can be increased after printing of ULTEM 9085 by a process of annealing. However, while this annealing does indeed increase the bond length, it actually decreases the strength of the bond as demonstrated in tensile tests. This indicates that bond length and bond quality are distinct factors affecting the bond strength (Graybill, 2010).

Experiments on FDM printing of ABS400 polymer have shown that most of the neck growth occurs at printer chamber temperatures exceeding 200 Celsius, and that maintaining the contact interface between filaments for extended periods of time, allows greater bonding to occur. Conversely, it has been demonstrated that at temperatures above 240 Celcius, the ABS will degrade significantly resulting in weaker bonds (Li, Sun, Bellehumeur, & Gu, 2002).

It has been shown that prediction of the bond length formation can be modeled by combining a Newtonian sintering model with a thermal/cooling model (Bellehumeu, Li, Sun, & Gu, 2004).

2.6.1 Filament Shape

Cooling and convective heat transfer is dependent on the geometry of the filament. Two geometric factors of importance are the perimeter of the filament as well as the cross sectional area. As filaments are elliptical in nature, their radii are defined as semi major and semi minor axis (figure 2.13).

The area is defined as:

$$A = \pi ab$$

The perimeter is defined as:

$$P = \pi(a + b) * \left(\frac{64 - 3\lambda^4}{64 - 16\lambda^2} \right)$$

Where

Figure 2.13 Filament cross section

a = semi-major axis

b = semi-minor axis

And

$$\lambda = \frac{a - b}{a + b}$$

(Bellehumeu, Li, Sun, & Gu, 2004)

2.6.2 Convective Heat Transfer Model

Now that the geometric terms have been defined, the heat transfer model can be examined.

This requires definition of the Nusselt number. The Nusselt number (Nu) which is the ratio of convective to conductive heat transfer perpendicular to surface of a fluid, or in this case, the filament boundary.

$$Nu = \frac{hD}{k}$$

Where k is the thermal conductivity, h is the convective heat transfer coefficient and D is the characteristic length (or the equivalent diameter) of the filament, and is given as:

$$D = \frac{4A}{P}$$

To define h (convection coefficient) it is required to have a value for the Nusselt number, which can be found from a cylinder undergoing free convection. This is representative of the filament inside the 3D printer chamber – the filament is cylindrical and the printer chamber is assumed to be experiencing free convection as there is negligible air flow.

Thus:

$$Nu = \left\{ \sqrt{Nu_o} + \left[\frac{\frac{Gr * Pr}{300}}{\left(1 + \left(\frac{0.5}{Pr} \right)^{9/16} \right)^{16/9}} \right]^{1/6} \right\}^2$$

Where

Pr = Prandtl number of air (ratio of viscous diffusion rate to thermal diffusion rate)

Gr = Grashof number:

$$Gr = \frac{g\beta(T_s - T_\infty)D^3}{\nu^2}$$

Where g =gravity, β =volumetric thermal expansion coefficient, D = characteristic filament length (equivalent diameter) of body being cooled, ν = kinematic viscosity.

These equations can be used to model the time-variant cooling of the filament within the 3D printer.

2.6.3 Cooling Equation

Next a temperature for the deposited filament is required (T)

$$T = T_\infty + (T_o - T_\infty)e^{-mt}$$

Where T_∞ is equal to the print chamber temperature, T_o is the temperature of extrusion, t equals time.

m is equal to:

$$m = \frac{\sqrt{1+4\alpha\beta-1}}{2\alpha}$$

And

$$\alpha = \frac{k}{\rho C}$$

$$\beta = \frac{hP}{\rho CA}$$

(Graybill, 2010)

2.6.4 Frenkel's Sintering Model (modified)

Sintering is the bonding of crystalline particles via a process of diffusion and randomisation. Attempts had been made since the early 1930's to characterise sintering behaviour mathematically, however, the first theoretical groundwork for sintering was laid down by J. Frenkel in his 1946 paper entitled "Viscous Flow of Crystalline Bodies under the Action of Surface Tension". In that paper, Frenkel describes how sintering is a process that occurs as a result of the viscous flow of particles (droplets) that are deforming under surface stress (Frenkel, 1945). In the original Frenkel model, sintering is a two-step process where the wetted area increases until the gaps between the particles are separated. During the second step, the gaps are overrun and the two particles become homogenous (Ristic & Milosevic, 2006). Pokluda et.al have modified this sintering model to make it better applicable to polymer sintering and in this model the variation of the particle radius over time is taken into consideration and considers the process beyond the two stages described by the original Frenkel model.

The modified version is as follows:

$$\frac{d\theta}{dt} = \frac{\Gamma}{a_o\eta} * \frac{2^{-5/3} \cos \theta \sin \theta (2 - \cos \theta)^{1/3}}{(1 - \cos \theta)(1 + \cos \theta)^{1/3}}$$

Where Γ is the coefficient of surface tension and $\frac{d\theta}{dt}$ is the change in sintering angle over time. The sintering angle is the angle of the intersection and the radius of the neck. As can be seen in figure 2.14, θ begins at zero when there is no contact, and as the neck grows, θ increases until the two droplets become one over time.

Figure 2.14 Evolution of neck growth of a filament (Graybill, 2010)

Finding $\theta(t)$ can be achieved by use of a Runge-Kutta-Fehlberg integration method, and once this has been determined it is possible to derive the neck radius (the length, or $2y$) (Bellehumeur, Pokluda, & Vlachopoulos, 1997).

2.7 Summary

It is shown that the strength of the bond is related to the length of the bond (the neck) in between the filaments, and that the length of the bond is related to the thermal history of the filament (Bellehumeur, Li, Sun, & Gu, 2004). Additionally it has been shown that the extrusion temperature has the largest impact on neck growth compared to the impact of the printer chamber temperature. Due to the cooling of the freshly extruded filament, the full strength of the raw material will never be achieved as the temperature of the chamber is below the glass transition temperature (Li, Sun, Bellehumeur, & Gu, 2002).

Figure 2.15 Interaction plot showing effects of factors on bond strength (Graybill, 2010)

2.8 Knowledge gaps

In addition, on the behaviour of bonding of thermoplastic filaments, there has been a knowledge gap identified in the sintering model, and also the modified version. The current 2-dimensional model is based on 2 particles of the same radius, and it does not consider particles of differing radii. It is postulated that if one of the particles (or filament cross sections) is smaller than the other, then this will reduce the bonding angle and will thus reduce the bonding neck length, which could begin to explain why the structures are weakened when cooled and reheated (as explored in chapter 4). A reduction in neck length would result in the reduction in the bonded area and subsequently, a reduction in strength. Regarding the findings in the Graybill paper, it is identified that bond length and bond quality contribute to the strength of the filament bond. The term “quality” is somewhat ambiguous, and this needs to be addressed if an accurate bonding model for filaments is to be constructed. The literature review has shown while bond length can be increased by post-process annealing, the annealing process has a detrimental effect on the bond quality and the strength of the bond. It is apparent that the strongest bonds occur if the print chamber is kept at temperatures above the glass transition temperature, although FDM printers generally maintain the chamber temperature below the glass transition temperature. The effects of thermal creep have also not been adequately modelled to this date, and research into this area would help to define a more accurate sintering model.

2.9 Conclusions

Based on the literature review, it can be concluded that the manufacturing industry is slowly moving towards implementing 3D printing for end use products rather than using additive manufacturing solely for prototyping. In addition it is seen that companies such as Nano Dimension and Voxel8 develop additive manufacturing systems that offer the ability to manufacture not only structures but also to print conductive tracks at the same time. This enables new PCB geometries to be printed and manufactured at the same time

as the structure, which can reduce weight by alleviating traditional PCB boards as the conductive tracks are integrated into the structure. Printing thermoplastic filaments and conductive tracks is still a long way off from what is required for the rapid autonomous manufacture of complete, complex systems however. Filaments and conductive inks can be extruded or jetted- but adding subsystems such as microcontrollers and other electronic devices still require installation in the structure and location on the conductive tracks.

Finally, it can be demonstrated that use of snap-fit clips can be used to reduce part inventory in larger assemblies and can also reduce assembly time. This can be beneficial in 3D printing, especially if two plastic shells need to be mated together without the need of further fasteners. From the literature review it is seen that FDM parts display anisotropic behaviour in terms of strength. This also applies to snap-fit clips. The print orientation of mating components in a snap-fit system can potentially increase the friction between the components, and can therefore increase the mating force required to join the parts together. A greater understanding of the friction of these parts combined with an accurate model for 3D printed beams can help to design optimised snap-fit clips which will deflect and remain intact with specified and predictable loads. Regarding the application of DFA methodology to a combined printing and assembly process, the key points to be taken into consideration are that embedded part counts should be minimised and consideration should be given to ease of handling. When embedding components in a hot printer chamber it is desirable to minimise human contact with the hot area for health and safety reasons, as well as to reduce contact with the printed foundation into which the components are embedded. Therefore components should be embedded with a simple downwards motion, and should require minimal fastening in order to reduce forces on the printed foundation. A flow chart has been created that encompasses these principles and can be found in Appendix D.

3. Drone Design and Manufacture

3.1 Drone Design

The drone project was conducted in collaboration with Stratasys, who were investigating the possibilities of embedding more complicated pieces of hardware inside FDM manufactured parts. Stratasys already have guidelines published on the embedding of simple hardware components such as metal washers and threaded inserts (StratasysDirect, 2014) and had previously conducted research on embedding simple RF structures within PolyJet manufactured structures (Dumene & Kennedy, 2015). This project was an extension of that, and was intended to push the envelope in terms of the complexity of the systems that could be embedded, and in particular with the ULTEM 9085 thermoplastic which requires a higher chamber temperature than other thermoplastics. Due to the increasing popularity in commercial UAVs, it was decided to produce a drone with this method, as it would not only push the envelope in terms of high temperature assembly but would also have marketing value to the company. The ultimate goal of the project, therefore, was to demonstrate that it was possible, in principle, to design a process and workflow that would allow the printing of strong, lightweight drones that were effectively capable of flight as soon as they came out of the printer.

3.1.1 Design Workflow

- 1) Determine drone size and mass
- 2) Calculate lift requirements for size and mass
- 3) Perform thermal bake tests on hardware
- 4) Final design and manufacture
- 5) Flight test

3.1.2 Drone Size

Drones come in a variety of sizes and generally speaking, the larger the drone, the larger the quantity and size of equipment it can accommodate. This means that larger batteries can be used which in turn means longer flight times. In summary, bigger is better, so the size of the drone in this project was determined by the maximum size of the Fortus 450mc 3D Printer print envelope size (406.40 x 355.60 x 406.40 mm) (Stratasys, 2014). The requirement to have maximum battery capacity also helped determine the dimensions of the drone (figure 3.1). All the other components fit within the envelope defined by these two factors.

The drone measured 400mm from propeller shaft to the opposite shaft across the diagonal. After the dimensions of the flight hardware requirements had been taken into consideration for the internal cavities, the density of ULTEM 9085 was inputted into the Solidworks material properties library and the mass analysis indicated a mass of 525.31 grams for the airframe and the battery cover.

Figure 3.1 Basic dimensions of ULTEM 9085 drone

The mass of the other components is shown in the table 3-1 below:

Table 5 Component mass table

Component	Quantity	Mass per unit	Total Mass (grams)
Airframe and battery cover	1	525.3	525.3
Cobra 2213 950kv 3-4S	4	65	260
Naze 32 Acro Flight Controller	1	5	5
Drone Matters HK Blue Series	4	39	156
Graupner E-PROP 10X5	4	12.6	50.4
Custom ULTEM battery plate	1	14.2	14.2
Custom ULTEM flight controller	1	12.6	12.6
Custom ULTEM receiver	1	6.6	6.6
Custom wiring harness and	1	20	20
ZIPPY Compact 6200mAh 3s	1	451	451
Futaba R3008SB Radio Receiver	1	13.8	
TOTAL			1514.9 g

3.1.3 Lift Requirements

With the baseline size and mass requirements defined it is possible to determine the thrust (lift) requirements. The simplified free-body diagram shows the forces required for vertical flight (figure 3.2).

Referring to figure 3.2, F_1 through F_4 are the forces generated by the 4 motors and propellers and L is the sum of those forces. Mg is the mass of the drone multiplied with gravity to yield the weight.

$$L = \sum_{i=1}^n F_i$$

$$Mg = 1.501kg * 9.81m/s^2$$

$$Mg = 14.72 \text{ Newtons}$$

In order to generate a static hover, the lift force (L) must be in principle equal to weight (Mg). To generate upwards acceleration, lift must be greater than weight. A lift-to-weight ratio of 2 was arbitrarily selected as this value will enable observations of the basic flight functions and to confirm that the systems such as the gyroscopes and accelerometers on the flight controller have survived the elevated temperature of the print process. This project was not concerned with in-depth analysis of flight dynamics or flight handling characteristics, only that the manufacturing process was a success. Had it been a flight dynamics focussed project, then the design of the propulsion requirements would have been more in depth.

Figure 3.2 Free body diagram of vertical forces on a quadcopter

With a lift-to-weight ratio of 2, a baseline target to aim for is provided in terms of lift capacity.

Thus, $2 * Mg = 29.44$ Newtons is the baseline. This is divided by 4 to get the requirement per motor (7.36 Newtons or 750.51 grams force).

Brushless DC motor performance data is widely published, and is largely based on experimental data, so it is preferred to use this existing data than to perform tedious and potentially inaccurate disk loading calculations. The motor manufacturer's data sheet (table 3.2) for the selected motor shows that with a similar sized propeller, this motor is capable of 861.5 grams force (8.45 N) at 100% throttle, providing more than enough lift to gain altitude.

Table 6 Cobra motor specifications (Innov8ive Designs, 2016)

Throttle	Motor (A)	Input (W)	Prop (RPM)	Thrust (g)	Efficiency (g/W)
10%	0.17	1.89	1234.00	27.90	14.79
20%	0.42	4.68	1972.00	65.50	13.98
30%	0.90	9.93	2713.00	127.80	12.86
40%	1.73	19.19	3503.00	205.30	10.70
50%	3.02	33.50	4265.00	311.90	9.31
60%	4.56	50.59	4920.00	418.20	8.27
70%	6.54	72.56	5528.00	537.00	7.40
80%	9.01	99.99	6113.00	664.40	6.64
90%	11.83	131.34	6636.00	788.00	6.00
100%	13.62	151.23	6907.00	861.50	5.70

Figure 3.3 Throttle vs. Thrust graph (Innov8ive Designs, 2016)

3.1.4 Thermal Bake Testing

Due to the fact that the electronic components were to be embedded in a sealed drone unit at high temperature, it was imperative to test these components at high temperature before the embedding process, as it would be difficult to retrieve them from a sealed unit if they had failed after being embedded.

A variety of electronic flight hardware components (ESCs and flight controller) were initially embedded into separate and discrete drone parts (individual rotor arms and a separate airframe) during initial test prints. The discrete test pieces can be seen in figure 3.4. A thermal time budget was applied to each component based on observed failures. The reason for testing the components in the printer rather than a dedicated oven, was to more accurately emulate the environment in which they would be subjected to during manufacturing. It also allowed a visual inspection for any damage that may occur from thermal mismatch between the plastic structure and also the electrical components. Detailed drawings of the component housing contact points can be seen in Appendix F. After the thermal budgets had been recorded then it was possible to select which components had a greater reliability for a certain amount of time and for specific temperatures (table 3.3). From that information, the drone internal structure could be determined to increase or decrease the time spent for each component in the heated environment.

Table 7 Component thermal budgets

Component	Test Temp (°C)	Thermal Budget (min)
Naze 32 Acro Flight Controller	160	300+
Drone Matters 2A ESC	160	200
Standard PVC harness/connectors	160	60
Modified wiring harness and connectors	160	300+
Futaba R3008SB Radio Receiver	160	25

After numerous hardware types were tested it was found that flight controllers containing advanced sensors such as GPS and barometers would fail due to these components, so it was decided to use more basic flight controllers with minimum functionality only containing the minimum sensors such as gyroscopes and accelerometers.

Figure 3.4 Early prototype printed in discrete pieces (rotor arm and airframe) and tested

3.1.5 Custom Housings and fittings

The OEM plastic housings for the Futaba receiver and the flight controllers had a tendency to melt after a very short period, so these housings were removed and replaced with custom housings, which were printed from ULTEM 9085.

The custom housings were multi-purpose:

- To provide a flat surface to permit extrusion of filament over the components
- To protect the hardware from the elevated extrusion temperature
- To provide an interface allowing easier installation during printing

In addition to the two custom housings, a battery plate was printed with ULTEM 9085 (figure 3.5), to enable the printing of a battery cavity inside the drone without the need for extra support material, which would have been problematic to remove.

The OEM wiring harness and connectors were problematic as well. These are all manufactured from PVC which begins to decompose at 140°C and has a melting point of around 160°C.

Figure 3.5 Custom housing illustrations

All wires containing PVC insulation were replaced by high-temperature silicone versions, and the connectors were all replaced with glass-filled polycarbonate connectors. This required some soldering, particularly in the case of the ESCs which had the original wiring soldered directly onto the circuit board.

Figure 3.6 Flight controller housing with wiring loom

3.2 Manufacture of Drone

When printing with the FDM process, normally it is required to use a separate support material in addition to the actual model material in order to print structures with an overhang over more than 45°. Support material is typically removed mechanically or with an alkaline heat bath which dissolves the support material over time.

Due to the complexity of the interior structure after the drone was complete, it would have been difficult to mechanically remove support material from the interior, and due to the electronic components it was decided that submerging the finished product in a heat bath was not an option, so the drone was designed to have zero support materials on the interior. It was decided to use self-supporting structures of 45° angles for the drone interior, and to use a separate battery plate to allow the creation of a battery cavity which would have otherwise collapsed without this plate. The only support material used was for the exterior of the drone, for supporting the propeller arms.

Before the final manufacture of the airframe and the embedding of electronics during the printing phase, some preparatory tasks were necessary.

- 1) Modify ESCs with silicone wiring insulation and polycarbonate connectors
- 2) Remove PVC connectors from flight controller
- 3) Connect ESCs to flight controller
- 4) Print custom battery plate, receiver housing and flight controller housing (ULTEM 9085)
- 5) Install flight controller and ESC assembly into custom flight controller housing (see figure 3.7)
- 6) Install Futaba receiver into custom receiver housing

In order to embed the electronics and seal them within the drone, the printer needed to be paused three times. The occurrence of each pause had been calculated in accordance with the thermal budgets of each component, so that components with the highest thermal

budget would be embedded earlier and components with low thermal budget would be embedded last. This meant that the components embedded last would be exposed to the print chamber temperature for the least possible time.

Figure 3.7 Custom ULTEM housing for Flight Controller

The embedding schedule with respect to the pauses was as follows:

- 1) During the first pause (at 5 hours 11 minutes) the battery plate was embedded.
- 2) At the second pause (at 9 hours 10 minutes), the Flight Controller, ESC, wiring harness and custom Flight Controller housing was embedded.
- 3) The third and final pause occurred at 13 hours 20 minutes. During this final pause, the receiver was embedded into the drone and was wired directly to the flight controller. This was left until last due to its high failure rate at the tested temperature.

Section 3.3 contains illustrations showing the embedding procedure (figures 3.8 to 3.11) and details of the manufacturing parameters and the toolpaths are shown in Appendix G.

3.3 Manufacturing Procedure Illustrations

Figure 3.8 Illustration of 1st pause embedding steps

Figure 3.9 Illustration of 2nd pause embedding steps

Figure 3.10 Illustration of 3rd pause embedding steps

Figure 3.11 Illustration of final assembly steps

3.4 Snap-fit Clip Design

As described in the literature review on snap-fit clips (section 2.4), snap-fit clips provide a convenient method of joining assemblies together without the need for extra fastening hardware. They can be designed into a component to be 3D printed with minimal increase in cost compared to injection moulded parts that would require expensive mold slides or other mechanisms in order to manufacture. Snap-fit clips were selected as the means of fastening the battery cover to the drone.

Figure 3.12 Snap-fit clips located on the drone body

Figure 3.12 shows the fastening mechanism of the battery cover in relation to the drone airframe. There is the none-load bearing top fastener which assists with locating the cover, and the two snap-fit hooks at the bottom of the cover, which deform when the cover is

fitted and pushed into place. The snap-fit hooks then return to the original position once they have cleared the undercut face, and the cover is then firmly attached to the airframe.

Figure 3.13 shows the dimensions of the snap-fit clip as designed for the drone. The height of the clip (not depicted in the 2D image) is $b = 8mm$.

Figure 3.13 2D drawing of clip dimensions (in millimetres)

The tensile elongation at yield (ϵ) of ULTEM 9085 is given as 6% according to the material data sheet (Stratasys, 2016). The permissible strain for short-term and single use of a snap-fit clip is 70% of that value, providing a value of 4.2% of permissible strain. For repeated use, such as that experienced by a snap-fit clip undergoing repeated loading cycles, a value of 50% of the permissible strain should be used as the maximum allowable strain for repeated use clips (Trantina & Ysseldyke, 1989). The maximum allowable strain (ϵ_0) for a snap-fit clip made from ULTEM 9085 is therefore 2.1% (0.021).

3.4.1 Design Methods

There are two methods for designing snap fit clips. The basic method for design is based on cantilever beam theory and is highlighted in the literature review in section 2.4. It is worth noting that the traditional design guidelines for snap-fits were intended for injection moulded plastics and also for machined or cut metal components, and not for additive manufacturing processes. As mentioned in the literature review, the print orientation of the part can have significant effects on the strength of the clip, as can the contour and raster orientation. Previous research (Klahn, Singer, & Meboldt, 2016) has determined the optimal contour configuration as shown in figure 3.14. The clips designed for this project have used this as a guideline and have followed the recommendations for contours accordingly.

Figure 3.14 Optimal contour paths for clips (Klahn, Singer, & Meboldt, 2016)

The first design method from Bayer Plastics (Bayer Material Science, 2010) defines y (permissible undercut, or deflection) for a uniform section beam as:

$$y = 0.67 * \frac{\varepsilon_o * l^2}{h}$$

Where:

$$\varepsilon_o = 0.021$$

$$l = 3 \text{ mm}$$

$$h = 1.5 \text{ mm}$$

$$y = 0.67 * \frac{0.021 * 3^2}{1.5}$$

$$y = 0.084 \text{ mm}$$

Many of these values are constant and cannot be changed. The thickness of the clip (h), is equal to the thickness of the drone wall in order to reduce sharp angles (steps) and stress concentrations. When using these values, the formula yields 0.08mm for the permissible undercut. This undercut value is not only below the dimensional accuracy of the Fortus 450mc printer ($\pm .127 \text{ mm}$), but it is smaller than the extruded filament track (0.51mm). It is clear that the Bayer design guidelines are not suitable for small clips, based on the dimensional capability of the Fortus printer. The Bayer design guide also does not take into consideration the deformation, stress and strain on the wall onto which the root of the snap-fit clip is mounted. It treats the wall as a completely rigid body. This can potentially give inaccuracies in terms of allowable loads and deformations. A 3D model of this design was created in Solidworks, and was simulated in Solidworks FEA with the wall fixed as a

Figure 3.15 Strain plot showing model designed with Bayer method

rigid body to illustrate how the Bayer method calculations affect the design of the part (figure 3.15).

The second design method by BASF does take into consideration the location and orientation of the clip with relation to the mounting surface, and introduces a deflection magnification factor into the equations (BASF Corporation, 2007). This factor is referred to as the Q factor, and provides the designer with a graph (figure 3.16) to help determine the factor best suited to the design, based on the aspect ratio and clip orientation.

The clip on the drone corresponds most closely to a type-5 clip as highlighted on the graph.

Figure 3.16 Q factor graph (BASF Corporation, 2007)

For a uniform section beam, the permissible undercut or deflection as defined by the BASF guidelines is defined as:

$$y = \frac{\varepsilon_o l^2 * Q}{1.5t} = \frac{0.021 * 3^2 * 5.5}{1.5 * 1.5} = 0.462 \text{ mm}$$

From the graph in figure 3.16, the value of Q is found by finding the aspect ratio (L/t) on the x-axis and tracing the curve for a type-5 clip. In this case the aspect ratio is 3/1.5 = 2, so the value of Q is 5.5. Using the same values as the first design method, the undercut value is equal to 0.462 mm:

As demonstrated the difference in the permissible deflection between the first and second design methods is significant. In practical terms, the deformation of the wall modelled in method 2 can contribute to the permissible deformation of the clip, and can allow a larger undercut to be designed within the limits of the permissible strain and within the dimensional capability of the printer. A second simulation was used to model the deformation based on the BASF method to show the difference in displacement when the wall is allowed to deform (figure 3.17), rather than being treated as a rigid body as was the case in the first method.

Figure 3.17 Strain plot showing model designed with BASF method

3.4.2 Deflection and Mating Force

Both methods use the same formula for calculating deflection force and mating force, with the exception that Bayer uses the secant modulus and the BASF method uses the flexural modulus of the material. However, both secant modulus and flexural modulus are both the same value up to the proportional limit of the material (Instron, 2017).

The deflection force is the force required to deflect the clip to the maximum deflection (y) is defined for both design methods as:

$$P = \frac{bt^2 E \varepsilon_o}{6L}$$

Where:

$$b = 8mm$$

$$t = 1.5mm$$

$$E = 2500 MPa$$

$$L = 3 mm$$

The deflection force to bend the clip to the strain limit for both methods is calculated as:

$$P = \frac{8 * 1.5^2 * 2500 * 0.021}{6 * 3} = 52.5 N$$

Similarly, the mating force for both methods uses the same formula as each other:

$$W = P \frac{\mu + \tan \alpha}{1 - \mu \tan \alpha}$$

Where:

$$\mu = \text{coefficient of friction} = 0.45$$

$\alpha = \text{angle of insertion} = 45^\circ$

Plugging in those values yields:

$$W = 52.5 \frac{0.45 + \tan 45}{1 - 0.45 \tan 45} = 138.40 \text{ N}$$

The size of feature printed by the Fortus 450mc printer is limited by the extrusion tip diameter. In the case of ULTEM 9085, a T16 tip is the only tip that can print this material. The T16 tip has a minimum extrusion path width of 0.016 inch (0.4064 mm) and a maximum extrusion path of 0.032 inch (0.8128 mm), although for larger features the contour can be repeated side-by-side to produce parts with larger features (StratasysDirect, 2016). Effectively there is no upper limit in terms of feature size (providing the part fits within the printer build envelope).

Figure 3.18 shows a line graph where the formulas for both design methods have been plotted to show the relationship between clip thickness and maximum deflection (undercut), while remaining under the maximum permissible strain of 2.1%. Each method has been plotted with 6 different clip lengths. The dotted lines represent the minimum path width that is possible with the T16 extruder tip, and thus shows a “zone of manufacturability”, represented by the grey area.

As seen in figure 3.18, all of the clips designed using the Bayer formula fall outside of the zone of manufacturability. Only 4 clip lengths designed with the BASF method (incorporating the Q factor of 5.5) falls into the grey zone of manufacturability for the required clip thickness and deflection. For the given requirements, the minimum clip length must be 1.5 mm. Longer clip lengths give a wider range of thickness and undercut within the manufacturability zone.

Figure 3.18 Deflection vs. thickness: (zone of manufacturability)

This demonstrates that when designing small clips with FDM manufacturing, the limitations on the design imposed by the path width will limit the choices where it comes to clip thickness. The clip must be over 0.4064 mm thick (with a single contour) and preferably must be at least 2 contours thick (0.8128 mm) in order to generate a continuous contour for the formation of the hook.

3.4.3 Simulation Plots

The clips on the drone were ultimately designed using the BASF method including the Q factor of 5.5 and were simulated using Solidworks FEA solver.

The strain plot shows that when the simulated static load of 52.5 N was applied to each clip, the clip roots stayed within the required strain limit of 2.1%. Note that the largest strain (0.017 or 1.7%) was focused on the base of the part (depicted in red and labelled “max” in figure 3.19).

Figure 3.19 Strain plot showing both drone clips on airframe

This was not accounted for in the manual calculations, as the Q factor graphs do not provide a solution for clips that are mounted in this manner. Due to the lower section of the clip being mounted at 90° to the base of the drone, it anchors the base of the clip and the clip itself experiences a torque-like deflection with the top part of the clip deforming more than the bottom part. This is shown in the displacement plot in more detail (figure 3.20). This does represent a gap in knowledge in the BASF design guidelines. The strain in this

region would be eliminated by locating the clip further along towards the midpoint of the plate (the clip should be moved upwards, relative to the orientation in figure 3.20).

Figure 3.20 Close-up of displaced clip

The main displacement plot (figure 3.21) shows the deformation of both clips under load and shows the deformation of the walls to which the clips are mounted to. The deformation of the walls distributes the strain from the root of the clip and provides a higher allowable strain at the clip root and higher displacement at the clip end.

Figure 3.21 Main displacement plot showing both clips

3.4.4 Conclusion

This chapter has demonstrated that the Bayer method of designing snap-fit clips yields values of strain that are inaccurate or misleading for manufacturing clips at this small scale.

The BASF method offers a design process that yields results closer to those found in FEA simulations because of the inclusion of the Q Factor, which takes into consideration the extra deflection and strain allowed by the deformation of the wall.

The presence of the torsion effect on the clip shown in figure 3.20, caused by the location of the clip with respect to the adjacent wall demonstrates a knowledge gap regarding the Q factor which could be explored in future.

Using the BASF method coupled with the FEA results, the real-life clip was printed with the drone, according to the optimum contour paths as recommended by previous research (Klahn, Singer, & Meboldt, 2016).

In reality, the finished product has shown no visible signs of failure or fatigue, and has completed over 100+ mating cycles in real life, non-laboratory conditions.

3.5 Evaluation of Drone

3.5.1 Electronics Systems

An access port was designed into the airframe to enable basic testing of the flight controller and the onboard sensors via the micro Naze32 USB port and a computer running the Baseflight Flight Control configurator / data logger before moving on to real life flight testing.

Baseflight allows for ground testing of gyroscopes, accelerometers, radio transmission, motor testing and ESC calibration.

Preliminary tests in Baseflight showed that all systems were performing nominally with no failures detected (figure 3.22).

Figure 3.22 BaseFlight configurator showing nominal gyroscope functionality

3.5.2 Structure

Overall the structure was sound and there were no defects, asides from 3 horizontal distortions corresponding to the layers at which the printer was paused. Two of these distorted layers can be seen in figure 3.23 This is not only an aesthetic fault but a mechanical one as well.

Previous tests had shown that there is a weakness at this bond layer, which occurs as a result of the printer door being opened and cooling occurring at that layer. This issue is investigated further in a chapter 4, and a factorial experiment has been devised to measure this loss in bonding strength based on certain printer operating conditions.

Figure 3.23 Distortion lines caused by cooling

3.5.3 Flight Tests

The Baseflight Configurator flight software was used for communication between the Naze32 Flight Controller and the PC laptop. Baseflight is used for tuning the PID algorithms, for updating the Flight Controller, for motor tests and control input adjustments from the radio controller.

The firmware on the Naze32 was flashed and updated to the latest version before any flight testing was performed.

3.5.3.1 PID Settings

PID stands for Proportional, Integral and Derivative, and the PID controller is a close loop control system (figure 3.24) within the Naze32 Flight Controller. It takes the output signals from the IMU (Inertial Measurement Unit) in the form of linear and angular acceleration values, as well as motor speed information, and it routes that information back into the controller, constantly adjusting for any errors occur (present), that are occurring over time (accumulation) and predicting errors that may occur in future (rate of change of error). Errors are corrected by adjusting the voltage to the motors to compensate depending on which axis the error is coming from, according to specified angular rates. It is an iterative process resulting from the constant feedback loop and this helps to maintain stability in the quadcopter. (Salih, Moghavvemi, Mohamed, & Gaeid, 2010)

Figure 3.24 Closed loop control architecture

The PID controllers are unique to each axis, so if there is adverse yaw detected, the corresponding motors alter their speed to compensate the torque, and the same applies for pitch and roll.

The PIDs are measured in seconds, and represent how long between signals for each path in the feedback loop.

The default settings for the Naze32 with the recent firmware are shown in table 3.4.

Table 8 Default values for PID

	Proportional	Integral	Derivative
Roll	4.0	0.030	23
Pitch	4.0	0.030	23
Yaw	8.5	0.045	0

3.5.3.2 ESC Calibration

Before first flight, the ESCs must be calibrated by placing the drone on a flat, level surface and the Baseflight ESC calibration procedure should be applied. When the ESCs are calibrated, an audible tone is generated signalling completion of calibration. This step was performed before the first flight.

3.5.3.3 Tethered Flight

The quadcopter was tethered to the floor by string, and was the string was anchored to the floor by weights. On arming the drone, and increasing throttle to the 80% mark, the quadcopter lifted slightly and began yawing and pitching with no manual input.

Figure 3.25 Motor layout

The drone was disarmed, and plugged back into Baseflight for alterations. After increasing the yaw PIDs it was found that there was no discernible difference in the yaw.

After lowering the minimum throttle activation threshold (to allow a smaller control input to get the motors spinning) it was noticed that motor number 4 was spooling up later than the other three motors. Figure 3.25 shows the layout and direction of the motors.

After recalibrating the ESCs, and testing a variety of PID values to better correct the yaw, it was deemed futile, and corrections had to be made to the inputs with the trim. The PID settings were restored to the default values.

It was concluded that the lag in spooling may have been caused by heat damage to that particular ESC. Although the ESCs have proven to be fairly resilient to high temperature (having the highest survivability / thermal budget of any component in the system), two of the ESCs (numbers 4 and 2) had been reused from an earlier prototype, and had experienced a greater number of heating and cooling cycles.

3.5.3.4 Final Flight Test

The adverse yaw had been compensated for with the trim and the flight test was conducted without the tether. The angle limiters were set to 45 degrees, and these were confirmed to be working by pushing the pitch and roll controls to their maximum inputs.

This indicates that the accelerometers and the gyroscopes were functioning in the flight test, as well as being confirmed in Baseflight.

The flight time for the first flight was 22 minutes.

3.5.4 Qualitative Analysis

Due to the decision to design and manufacture the drone with a basic Flight Controller, the autonomous capabilities normally associated with drones were not present.

As there was no GPS or barometer it was impossible to maintain a position hold, an altitude hold or any other advanced flight modes such as loitering or waypoint navigation.

The gyroscopes were able to maintain level flight, and the accelerometers were able to measure speed however.

In terms of flight performance, the flying experience was very much *pilot-in-the-loop* due to the lack of autonomous function.

As predicted during the motor selection process, around 80-90% of throttle was needed to achieve lift off. This made the handling qualities in the vertical axis very unresponsive due to the weight of the drone. It is concluded that this could only be corrected with more powerful motors, or with a lighter airframe.

3.5.5 Cooper-Harper Rating

The Cooper-Harper rating scale is a qualitative ranking used by test pilots for communicating how easy or difficult or simple it is to control an aircraft.

Figure 3.26 Cooper-Harper scale flow diagram (NASA, 1997)

Referring to figure 3.26, and based on several flight tests, the following observations can be drawn:

- Is it controllable?
Yes
- Is adequate performance attainable with tolerable pilot workload?
Yes
- Is it satisfactory without improvement?
No

The aircraft characteristics fall into a category 6 for *pilot rating*. This means that the aircraft characteristics were *very objectionable but tolerable* and the demands on the pilot required *extensive pilot compensation* in order to *achieve adequate performance*.

This is largely a result of the weight of the quadcopter, and the lack of a barometer which prevented autonomous altitude hold.

3.6 Concluding Remarks

The goal of this project was twofold in nature. It was intended to demonstrate the ability to embed electronics in a high-temperature environment, while at the same time making an attractive product to be used by Stratasy's for marketing purposes. The addition of curves to the geometry for aesthetics combined with the requirement for self-supporting angles internal to the structure resulted in an attractive but overweight product. This extra weight combined with the lack of autonomous functions meant that the drone was difficult to operate in terms of handling.

Future iterations could sacrifice aesthetics and lose several hundred grams in mass. The loss of mass would result in a reduction in printing time, and could therefore potentially accommodate more advanced electronics which are sensitive to long duration exposure to high temperature, such as GPS and barometers.

4. Chapter 4: Bond Strength Experiment

4.1 Background

During the construction of the drone prototype it was observed that a visible seam appeared at the paused layer upon resuming the print after the hardware had been embedded. This effect was not only aesthetic in nature but resulted in a weakened bond layer and it is theorised that this effect is a result of the part cooling while the print chamber door is opened for the embedding process to occur.

This experiment is designed to investigate the effects of cooling on filament bond strength when the printer is paused, and the door opened in order to embed hardware into the printed structure.

The following factors will be investigated:

- Initial print chamber temperature
- Cooling temperature during open door
- Effect of prolonged reheating

The following responses will be investigated:

- Bond strength between filaments at weakened layer
- Bond Length at weakened layer
- Strain and Young's Modulus at weakened layer

It is hypothesised that reheating the part before resuming the printing may help to recover some of the strength of the part. The bond strength can be determined by measuring the tensile strength of the specimen and will show the ability of the bond layers to withstand the applied load before failure.

The tensile strength of the specimen can be determined with the following formula:

$$\sigma = F/A$$

Where σ is the tensile strength, F is the force at break and A is the cross sectional area of the specimen. In this experiment the cross sectional area will be determined by multiplying the bond length (determined with optical microscope analysis) with the width of the specimen. The strain of the specimen is the ratio of elongation compared to its original length, and is described mathematically as:

$$\varepsilon = \Delta L/L$$

Where ε is the strain, ΔL is the change in length (elongation) and L is the original length.

The Young's modulus of the samples will also be assessed. Young's modulus is the property describing the elasticity of the material and is defined as the ratio of stress to strain:

$$E = \sigma/\varepsilon$$

Where E is Young's modulus, σ is stress and ε is strain.

Generally when testing polymer specimens, a “dog bone” style test sample is used (Wong, Chua, & Yeong, 2017). However, in this case, as the specimens are very thin, rectangular specimens will be used, with the addition of tabs adhered to either end in order to reduce stress concentrations. Printing a dog bone shape would require the use of support material which would prevent temperature measurements being taken of the substrate material while in the printer. Additionally, removing the support material would require extra handling which could potentially cause weakening of the specimens and cause a skewing of the results. All of the results will be taken from the data logging software which measures the forces and breakage point of the specimens and provides the calculated tensile data in a numerical format ready for further analysis in Mintab and Excel.

4.2 Experiment Preparation

- 1) First a CAD model of the following dimensions is designed in Solidworks, and is exported as a .STL file (figure 4.1).
- 2) The .STL file is imported into Stratasys Insight slicing software, and a pause is added to layer 306. There are 600 layers in the model in total, plus 6 foundation layers which are removed afterwards. The 306th layer is midway up the z-axis.
- 3) In the Insight software there is an option to select a *thin-walled* model or a *normal* model. Select the normal option and save the CMB file. Then select the *thin-walled* option, and save the file as a different filename. This provides us with 2 oven temperature settings.
- 4) Open the Stratasys Control Center software, and load the CMB file specific to the experiment requirement. Export the job to the Fortus printer.

Figure 4.1 Dimensions of 3D printed tube (left), dimensions of trimmed tensile coupon and tabs (right)

- 5) On the Fortus control panel, position the job in the centre of the print chamber.
- 6) Add the build sheet to the printer platform.
- 7) When the control panel indicates that the vacuum is ready, the print can begin.

4.3 Experiment Procedure

First Printing Phase (Phase 1)

- 1) Set up the NEC TH9100WL thermo tracer and the Tenma 72-873 IR / Optical thermometer as shown in figure 4.2.
- 2) When ready, press the *play* icon on the Fortus touchscreen control panel to start the print.
- 3) Wait for the print job to pause. The printer will stop and the touchscreen will display the status that the printer has been paused.

Figure 4.2 Layout of monitoring equipment

Cooling Phase (Phase 2)

- 1) Start the thermal tracer before the door is opened. Ensure that it is pointed at the printed part (figure 4.3).
- 2) Open the printer chamber door and begin the stopwatch.
- 3) Use the IR thermometer to take a reading of the topmost layers of the printed part. Make note of the part temperature and log the oven temperature from the Fortus control panel.
- 4) Take both readings every 60 seconds until the part has cooled to one of the 2 levels dictated by the experiment run requirements (80°C or 100°C). Each experiment run should be cooled down to one of the 2 temperatures.
- 5) When the part has cooled to the required temperature level, log the time taken to reach that temperature, and also log the final oven temperature.

Figure 4.3 Build chamber and part location

Reheat Phase (Phase 3)

- 1) Restart the stopwatch and close the printer chamber door.
- 2) Log the oven temperature every 60 seconds until the printer chamber has reached the steady state (either 160°C or 170°C depending on the experiment run).

Second Printing Phase (Phase 4)

- 1) Pressing the *play* button on the Fortus control panel will resume the print after a delay of 2 minutes and 5 seconds. Depending on the specific experiment run parameters, the play icon should be pressed as soon as the steady state has been reached, or 8 minutes after the steady state has been reached (use the stopwatch to time the 8 minutes). This will result in a steady state time of either 2.05 minutes or 10.05 minutes in total.
- 2) The printer will resume printing and the specimens can be removed upon completion.

Figure 4.4 Example of experiment thermal profile

4.4 Sample Preparation

The printed specimens will be in a self-supporting square prism shape and need to be cut to the correct shape and size (see figure 4.1) before the microscopy and tensile tests can be performed. In addition, small tabs must be manufactured from ULTEM 9085 and bonded to the ends of the specimens with Araldite epoxy resin in order to reduce stress concentrations during the tensile tests, and to ensure equal stress along the length of the specimen (figure 4.5).

Figure 4.5 Printed tubes (left), sliced specimens and stress relief tabs (centre), finished specimens (right). The arrow indicates the visible weakened bond layer, caused by pausing the print mid-way and allowing it to cool.

After the specimens have been manufactured into test coupons they should be examined under the Olympus SZX7 stereo microscope to determine the bond length of the layer of interest, and also to determine the average bond length of each specimen. The bond length will be used in calculating the area of the bonded layer and from that area the tensile strength can be determined.

The following steps were taken in examining the specimens:

- 1) Place the specimen in the custom holder so the thinnest side is facing the optics.
- 2) Set the microscope to 0.8 magnification to identify the bond layer of interest. Use the imaging software to capture this image.
- 3) Switch the microscope to 4.0 magnification and zoom in on the bond layer. Capture the image.
- 4) Using the imaging software, use the measurement tools to measure the bond length of the layer of interest, and also 3 layers above and beneath it (figure 4.6).
- 5) Remove the specimen from the microscope bed, flip it over and repeat for the other side.
- 6) Record the width of each specimen, and the gauge length.

Figure 4.6 Microscope image of bond layers

4.5 Tensile Test Procedure

After all measurements of the specimens were taken, the tensile tests were performed on the specimens, using a 10kN load cell and a strain rate of 1mm/minute.

The TrapeziumX data logging software was used for measurement and the Instron 5569 universal test machine was used for the tensile tests.

The following steps were taken in conducting the test procedure:

- 1) Define test parameters in TrapesiumX software (tensile test method, strain rate, graph outputs)
- 2) Enter specimen-specific dimensions into TrapesiumX software.
- 3) Mount specimen into grippers
- 4) Run the test
- 5) Log results for breaking stress, strain and force in spreadsheet
- 6) Export pdf summary and raw data for each sample
- 7) Repeat from step 2 for each sample.

Preliminary Observations

All of the specimens that had been subjected to the experimental treatments broke at the midpoint as predicted, indicating that there was a weakness in that particular bond layer resulting from the various factor treatments. The baseline samples which had been printed at the two oven temperature levels, without a pause and without reheating fractured in a random manner, suggesting that the bond layers all had a uniform strength, as predicted (figure 4.7).

Figure 4.7 Universal test machine (left), random fracture on untreated specimen (top right) and fracture of treated specimen (lower right)

4.6 Heating and Cooling

During phase 1, the oven remained at the steady state value of either 160°C or 170°C, depending on the experiment parameters. Larger parts tend to be printed at the 170°C setting whereas thin parts require the lower setting of 160°C in order to prevent the warping of the thin sections from excessive heat. The temperature during phase 1 is monitored via the printer control panel, which takes the temperature information of the oven from thermocouples positioned within the printer chamber. At the pause layer, the printer door is opened to allow the oven and the part to cool. At this point, 3 temperature readings are taken. The first reading uses the IR thermometer to take the temperature of the top layers of the printed part. The second reading uses the thermal tracer to take a thermographic image of the part and also the surroundings within the oven. The final reading is taken from the oven. The thermal tracer and the IR thermometer are only useful when the printer door is open. When the door is closed, the IR thermometer and the thermal tracer cannot measure the part through the glass on the door- they only read the actual temperature of the exterior door glass itself. The combination of these readings has been integrated to provide a history of the thermal parameters at the various phases of the experiment and have been plotted in thermal profile graphs (figure 4.8). The thermal images have been arranged to show how heat flows from the printer when the door is open.

Figure 4.8 Example of experiment thermal profile

Figure 4.9 Thermal image sequence of cooling part

These images show the heat loss from the oven set at 160°C. Once the printer door is opened, heat loss through convection towards the opened door begins immediately. The first image shows the heat loss from the oven 2 seconds after the door is opened.

25 seconds later, the face of the part closest to the open door (the front face of the part) is cooling down more quickly than the sides of the part. The printing platform cools at a much slower pace, due to the presence of heaters within the build platform.

50 seconds after the door has been opened, the top layers of the part have dropped to $\approx 125^{\circ}\text{C}$, as confirmed by the readings taken with the IR thermometer. Cooling from the oven walls is beginning to become visible.

At 1 minute, 16 seconds the front face of the part is cooling the fastest and the two sides parallel to the interior walls are cooling more slowly. As these sides are both cooling at approximately the same rate, it is decided to use these sides in the sample preparation.

Figure 4.10 Continued thermographic sequence

At 1 minute 40 seconds the front face is dropping below the current scale setting of the thermal tracer. The scale can be reset at this point, in order to detect the lower temperatures. There is a temperature difference of $\approx 15^{\circ}\text{C}$ between the sides of the part and the front face.

This image was taken approximately 2 minutes after the door was opened. The top layers of the part read in the range of $110\text{--}115^{\circ}$ according to the IR thermometer, and the oven temperature reads around 100°C according to the control panel. The thermal camera shows that this oven temperature is not uniform.

At approximately 2 minutes and 30 seconds the top layers on the side faces of the part have cooled to around 105°C , and the heat is visibly dissipating from the side walls of the printer, with the corners of the printer cooling at a slower rate.

3 minutes after the door is opened, the front face of the part has dropped below 104°C and the build platform is showing a loss of heat. The centre of the side walls of the printer chamber are cooling faster than the corners and the edges of the walls.

Figure 4.11 Final images of thermographic sequence

At ≈ 5 minutes the printed part has dropped to 80-85°C according to the IR thermometer, and is no longer detected in this particular image. The oven temperature has dropped to 75-80°C, and the thermal camera is showing the build platform is cooling down slowest.

At 5 minutes and 30 seconds the temperature of the printer walls is beginning to drop below the scale.

At 6 minutes recorded part temperatures of between 74-77°C are recorded by the IR thermometer and 70-74°C for the oven. The thermal camera is still showing a temperature of around 125°C for the build platform.

≈ 9 minutes after the door is opened, the scale is reset and the part has dropped to around 70°C on the top layers. The build platform is around 120°C and the printer walls are around 90-100°C. The cooling behaviour has remained consistent, and cooling rates of the part and oven have slowed as it approaches steady state.

4.7 Experiment Results and Analysis

4.7.1 Overview

The experiment was designed as a randomised 2^k factorial experiment (where $k=3$). The results data (bond length, stress at break, strain at break and Young's modulus) was all added to Minitab statistical software along with the corresponding experiment treatment parameters in order to perform the statistical analyses. In this experiment, there are 3 factors (A, B and C), and each factor has a , b and c levels respectively. R is equal to the total number of runs, and n is equal to the number of observations (replicates) per run. The grand total number of observations in the experiment is equal to N . In summary:

A= Oven Temperature, B= Cooling Temperature, C= Reheat Time

$a = 2, b = 2, c = 2$

$n = 3$

$R = abc = 8$

$N = Rn = abcn = 24$

Table 9 Factor descriptions and factor levels

Factor	Factor Description	Low	High
A	Oven Temperature	160°C	170°C
B	Cooling Temperature	80°C	100°C
C	Reheat Time	2.05 minutes	10.05 minutes

This experiment will examine: 3 main effects (A, B, C) and 3 two-factor interactions (AB, AC, BC). There was no significant 3-way interaction observed.

The experiment cube plot takes the general form as shown in Figure 4.12.

Figure 4.12 General form of cube plot (Montgomery, 2001)

Table 10 Randomised experiment table showing all possible treatment combinations

Std	Run	Oven Temp	Reheat Time	Part Cooling	Bond	Strength	Strain	Youngs Modulus	ID
Order	Order	(°C)	(m)	Temp (°C)	Length (µm)	(Mpa)	(%)	(Mpa)	
20	1	160	10.05	100	492.207	29.63	1.84	1610	7(c)
15	2	170	10.05	80	493.345	35.27	1.9	1856	4b(b)
4	3	160	10.05	100	527.74	27.32	2.1	1301	7(a)
16	4	170	10.05	100	618.15	35.9	2.74	1310	2(b)
8	5	170	10.05	100	540.925	22.64	1.24	1826	2(a)
2	6	160	2.05	100	465.157	26.96	1.43	1885	5(a)
13	7	170	2.05	80	543.23	36.53	2.18	1676	3b(b)
6	8	170	2.05	100	500.96	38.42	2.34	1642	1(a)
17	9	160	2.05	80	488.22	31.11	1.64	1897	6b(c)
9	10	160	2.05	80	496.875	22.83	1.23	1856	6b(b)
3	11	160	10.05	80	570.955	18.99	1.16	1637	8b(a)
18	12	160	2.05	100	479.295	24.21	1.28	1891	5(c)
21	13	170	2.05	80	563.12	34.82	2.1	1658	3b(c)
11	14	160	10.05	80	505.955	28.68	1.16	2472	8b(b)
10	15	160	2.05	100	471.02	29.71	1.58	1880	5(b)
1	16	160	2.05	80	506.625	28.32	1.54	1839	6b(a)
12	17	160	10.05	100	456.675	31.94	1.58	20.22	7(b)
23	18	170	10.05	80	546.925	28.59	1.66	17.22	4b(c)
22	19	170	2.05	100	587.8	38.16	2.75	13.88	1(c)
7	20	170	10.05	80	520.135	31.93	1.78	17.94	4b(a)
14	21	170	2.05	100	523.72	28.04	1.63	17.20	1(b)
19	22	160	10.05	80	538.455	23.83	1.38	17.27	8b(c)
24	23	170	10.05	100	579.537	29.27	1.99	14.91	2(c)
5	24	170	2.05	80	496.73	37.47	2.13	17.59	3b(a)

4.7.2 ANOVA

After the experiment has been designed and the results have been gathered, ANOVA can be used to analyse the variance between the sample group means to determine if a factor or factor interaction has an effect on a response. The P-value or the F-Value (with an F-table) is used to determine if the difference in means is significant enough to say that the factor level is correlated to the response output (Montgomery, 2001). A low P-value indicates that the chances of the response occurring for the specified inputs randomly are statistically unlikely, and any null hypothesis can be rejected.

Table 11 ANOVA formulae (Montgomery, 2001)

Source of variation	Sum of squares	Degrees of freedom	Mean square	F0
A	SS_A	$a - 1$	$SS_A / (a - 1)$	MS_A / MS_E
B	SS_B	$b - 1$	$SS_B / (b - 1)$	MS_B / MS_E
C	SS_C	$c - 1$	$SS_C / (c - 1)$	MS_C / MS_E
AB	SS_{AB}	$(a - 1)(b - 1)$	$SS_{AB} / (a - 1)(b - 1)$	MS_{AB} / MS_E
AC	SS_{AC}	$(a - 1)(c - 1)$	$SS_{AC} / (a - 1)(c - 1)$	MS_{AC} / MS_E
BC	SS_{BC}	$(b - 1)(c - 1)$	$SS_{BC} / (b - 1)(c - 1)$	MS_{BC} / MS_E
ABC	SS_{ABC}	$(a-1)(b-1)(c-1)$	$SS_{ABC} / (a-1)(b-1)(c-1)$	MS_{ABC} / MS_E
Error	SS_E	$abc(n - 1)$	$SS_E / abc(n - 1)$	
Total	SS_T	$abcn - 1$		

As the Minitab software was used for the statistical analysis, it is redundant to show the hand calculations for every factor or response in question. However, when performing the ANOVA, Minitab uses the adjusted sum of squares (Adj SS), also known as a Type III ANOVA (variance = average squared distance to mean).

The manual calculations for the Type III ANOVA performed on the tensile strength response are shown below as an example, and the computer generated results are used for all other responses.

Table 12 Results of experiment treatments, and calculated data means

Factor A	Factor B												y _{i...}
	80°C						100°C						
	Factor C						Factor C						
	2.05 minutes			10.05 minutes			2.05 minutes			10.05 minutes			
160°C	28.32	22.83	31.11	18.99	28.68	23.84	26.96	29.71	24.21	27.32	31.94	29.63	323.54
170°C	37.47	36.53	34.82	31.93	35.27	28.59	38.42	28.04	38.16	22.64	35.90	29.27	397.04
y _{.jk.}	191.08			167.3			185.5			176.7			
y _{.j..}	358.38						362.2						720.58=y...

$$SS_A = \sum_{i=1}^a \frac{y_{i...}^2}{bcn} - \frac{y_{i...}^2}{abcn} = \frac{(323.54)^2 + (397.04)^2}{2 * 2 * 3} - \frac{(720.58)^2}{2 * 2 * 2 * 3} = \mathbf{225.1}$$

$$SS_B = \sum_{j=1}^b \frac{y_{.j..}^2}{acn} - \frac{y_{.j..}^2}{abcn} = \frac{(358.38)^2 + (362.2)^2}{2 * 2 * 3} - \frac{(720.58)^2}{2 * 2 * 2 * 3} = \mathbf{0.6}$$

$$SS_C = \sum_{j=1}^b \frac{y_{.jk.}^2}{abn} - \frac{y_{.jk.}^2}{abcn} = \frac{(191.08 + 185.5)^2 + (167.3 + 176.7)^2}{2 * 2 * 3} - \frac{(720.58)^2}{2 * 2 * 2 * 3} = \mathbf{44.2}$$

$$SS_{AB} = \sum_{i=1}^a \sum_{j=1}^b \frac{y_{ij..}^2}{cn} - \frac{y_{i...}^2}{abcn} - SS_A - SS_B = \frac{(153.77)^2 + (204.61)^2 + (169.77)^2 + (192.43)^2}{2 * 3} - \frac{(720.58)^2}{2 * 2 * 2 * 3} - 225.09 - 0.61 = \mathbf{33.1}$$

$$SS_{AC} = \sum_{i=1}^a \sum_{k=1}^c \frac{y_{i.k.}^2}{bn} - \frac{y_{i...}^2}{abcn} - SS_A - SS_C = \frac{(163.14)^2 + (213.44)^2 + (160.40)^2 + (183.60)^2}{2 * 3} - \frac{(720.58)^2}{2 * 2 * 2 * 3} - 225.09 - 44.23 = \mathbf{30.6}$$

$$SS_{BC} = \sum_{j=1}^b \sum_{k=1}^c \frac{y_{.jk.}^2}{an} - \frac{y_{.jk.}^2}{abcn} - SS_B - SS_C = \frac{(191.08)^2 + (167.3)^2 + (185.5)^2 + (176.7)^2}{2 * 3} - \frac{(720.58)^2}{2 * 2 * 2 * 3} - 0.61 - 44.23 = \mathbf{9.4}$$

$$SS_{ABC} = \sum_{i=1}^a \sum_{j=1}^b \sum_{k=1}^c \frac{y_{ijk}^2}{n} - \frac{y^2 \dots}{abcn} - SS_A - SS_B - SS_C - SS_{AB} - SS_{AC} - SS_{BC}$$

$$= \frac{(28.32)^2 + (22.83)^2 + \dots + (29.27)^2}{3} - \frac{(720.58)^2}{2 * 2 * 2 * 3} - 225.09 - 0.61$$

$$- 44.23 - 33.1 - 30.6 - 9.35 = \mathbf{21.2}$$

$$SS_T = \sum_{i=1}^a \sum_{j=1}^b \sum_{k=1}^c \sum_{l=1}^n y_{ijkl}^2 - \frac{y^2 \dots}{abcn}$$

$$= (28.32)^2 + (22.83)^2 + \dots + (29.27)^2 - \frac{(720.58)^2}{2 * 2 * 2 * 3} = \mathbf{656.4}$$

$$SS_E = SS_T - SS_A - SS_B - SS_C - SS_{AB} - SS_{AC} - SS_{BC} - SS_{ABC}$$

$$= 656.4 - 225.09 - 0.61 - 44.23 - 33.1 - 30.6 - 9.35 - 21.2$$

$$= \mathbf{292.2}$$

Table 13 Calculated values for ANOVA

Source of variation	Sum of squares	Degrees of freedom	Mean square	F ₀
A	$SS_A = 225.1$	$a - 1 = 1$	$SS_A / (a - 1) = 225.1$	$MS_A / MS_E = 12.33$
B	$SS_B = 0.6$	$b - 1 = 1$	$SS_B / (b - 1) = 0.6$	$MS_B / MS_E = 0.03$
C	$SS_C = 44.2$	$c - 1 = 1$	$SS_C / (c - 1) = 44.2$	$MS_C / MS_E = 2.42$
AB	$SS_{AB} = 33.1$	$(a - 1)(b - 1) = 1$	$SS_{AB} / (a - 1)(b - 1) = 33.1$	$MS_{AB} / MS_E = 1.81$
AC	$SS_{AC} = 30.6$	$(a - 1)(c - 1) = 1$	$SS_{AC} / (a - 1)(c - 1) = 30.6$	$MS_{AC} / MS_E = 1.67$
BC	$SS_{BC} = 9.4$	$(b - 1)(c - 1) = 1$	$SS_{BC} / (b - 1)(c - 1) = 9.4$	$MS_{BC} / MS_E = 0.51$
ABC	$SS_{ABC} = 21.2$	$(a - 1)(b - 1)(c - 1) = 1$	$SS_{ABC} / (a - 1)(b - 1)(c - 1) = 21.2$	$MS_{ABC} / MS_E = 1.16$
Error	$SS_E = 292.2$	$abc(n - 1) = 16$	$SS_E / abc(n - 1) = 18.3$	
Total	$SS_T = 656.4$	$abcn - 1 = 23$		

4.7.3 Minitab Analysis

Plugging in the responses and factors into Minitab and running the general linear model function will produce the same (two-way) ANOVA table as shown in table 4-5, but with the addition of a P-value, which assists with quickly identifying the significant effects.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Oven Temp	1	225.155	225.155	12.33	0.003
Part Cooling Temp	1	0.611	0.611	0.03	0.857
Reheat Time	1	44.255	44.255	2.42	0.139
Oven Temp*Part Cooling Temp	1	33.112	33.112	1.81	0.197
Oven Temp*Reheat Time	1	30.578	30.578	1.67	0.214
Part Cooling Temp*Reheat Time	1	9.363	9.363	0.51	0.484
Oven Temp*Part Cooling Temp*Reheat Time	1	21.188	21.188	1.16	0.297
Error	16	292.150	18.259		
Total	23	656.410			

Model Summary			
S	R-sq	R-sq(adj)	R-sq(pred)
4.27310	55.49%	36.02%	0.00%

Figure 4.13 Minitab ANOVA results for strength

Any P-Values below the alpha value of 0.05 are deemed to be statistically significant. It has been shown that the most significant influence on the bond strength comes from the oven temperature factor, which has a P-Value of 0.003.

From the F table it is shown that the value for F_{α, v_1, v_2} ($F_{0.05, 1, 16}$) is equal to 4.4940. Therefore, as $F_0 > F_{\alpha, v_1, v_2}$ it can be concluded that the effect of oven temperature on bond strength is statistically significant at $\alpha=0.05$. The value for R-sq shows that the model accounts for 55.49% of the variance for the response under examination.

Before any conclusions can be made from the ANOVA, some checks regarding the independence of the samples, the normality of the residuals and the constant variance must be made.

4.7.3.1 Effects of Factors on Bond Strength

The normal probability plot of the residuals for strength (figure 4.14) shows that the residuals generally follow a normal distribution. The residual versus fitted values plot (figure 4.15) shows the residuals are randomly distributed, with similar variability and no outliers. The analysis shows constant variance.

Figure 4.14 Normal plot of residuals for strength

Figure 4.15 Residuals versus fitted values for strength

The residuals versus order plot (figure 4.16) shows that there is no pattern or correlation between the residuals. This indicates a random distribution around the zero mark, and therefore the residuals are independent of each other.

Figure 4.16 Residual versus observation order plot for strength

It can therefore be concluded that the ANOVA satisfies the specified requirements and the results can be accepted as the sample distributions show independence of the samples, the normality of the residuals and constant variance.

From the normal plot of the standardized effects at the 0.05 level, it is shown that the only significant factor affecting the ultimate tensile strength of the specimens is the oven temperature, with the other factors having no statistically significant effect. This is also confirmed by the Pareto chart (figure 4.17).

Figure 4.17 Pareto chart for strength

Although the Pareto chart and normal plot shows that the only statistically significant factor influencing the strength is the oven temperature, there is a trend that indicates some influence from the other factors. Examining the main effects plot, it can be seen that the highest strength specimens resulted from a combination of the highest oven temperature (170°C), the shortest reheat time permitted (2.05 minutes) after the oven has reached the steady state, and the highest cooling temperature (100°C). While not statistically significant, the effects may be *practically* significant, so can not be ignored, and they do confirm the prediction made in previous studies that indicate that reheating or specimens can have a detrimental effect on the sample strength (Graybill, 2010).

The main effects plot for strength (figure 4.18) shows a significant increase in strength for changes in oven temperature and a decrease in strength depending on the reheat time.

Figure 4.18 Main effects plots for strength

The interaction plot of the fitted means for strength (figure 4.19) shows interactions for *oven temp*part cooling temp* and also for *reheat time*part cooling temp*, but these are not shown to be statistically significant at the 95% confidence interval. Note: As the experiment features an equal number of replicates for each run, the fitted means are exactly the same as the data means (Montgomery, 2001).

Figure 4.19 Interaction plots for strength

Figure 4.20 Normal plot of standardised effects for strength

The normal plot of the standardised effects for strength (figure 4.20) shows negative effects to the left hand side of the diagonal line and positive effects to the right. Effects close to the line are said to be statistically insignificant while the effects furthest from the line (strength) are significant.

Figure 4.21 Bar graph showing mean strength

A bar graph was created from the raw data in Excel (figure 4.21), and each treatment combination was plotted on the x-axis with the tensile strength (at break) plotted on the y-axis. The treatment results (blue bars) were plotted against the average values from the separate baseline results (orange bars) to show the increase or decrease in strength from the treatment samples compared to untreated specimens.

The untreated maximum stress in this experiment measured at 35.69 MPa for samples printed in the 170°C oven and 28.53 MPa for those printed in the 160°C oven temperature.

Previous research conducted by Bagsik et al (figure 4.22) showed an average maximum stress of ≈ 41 MPa for samples printed in the z-axis orientation (Bagsik, 2011). Graybill et al shows an average maximum stress of 55.72 MPa for untreated specimens (Graybill, 2010). The variation between results can likely be explained by different sample preparation and measurement methodologies.

Figure 4.22 Tensile strength of specimens based on print orientation (Bagsik, 2011)

4.7.3.2 Effects of factors on Bond Length

The ANOVA results (figure 4.23) show that oven temperature has a significant effect on bond length with a P-value of 0.004. Additionally, the factor interaction AC (oven temperature*cooling temperature) has a P-value of 0.018. As both of these values are below the threshold of 0.05, they are to be considered as statistically significant effects. The combined residual plots (figure 4.24) show independence of the samples, the normality of the residuals and constant variance, so the ANOVA requirements are valid.

Analysis of Variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Oven Temp	1	11068.1	11068.1	11.28	0.004
Part Cooling Temp	1	31.2	31.2	0.03	0.861
Reheat Time	1	2998.3	2998.3	3.06	0.100
Oven Temp*Part Cooling Temp	1	6753.5	6753.5	6.88	0.018
Oven Temp*Reheat Time	1	427.9	427.9	0.44	0.518
Part Cooling Temp*Reheat Time	1	470.9	470.9	0.48	0.498
Oven Temp*Part Cooling Temp*Reheat Time	1	2229.2	2229.2	2.27	0.151
Error	16	15702.3	981.4		
Total	23	39681.6			

Model Summary			
S	R-sq	R-sq(adj)	R-sq(pred)
31.3272	60.43%	43.12%	10.97%

Figure 4.23 Minitab ANOVA results for bond length

Figure 4.24 Residual plots for bond length

Figure 4.25 Pareto chart of standardized effects for bond length

The Pareto chart for the standardized effects (figure 4.25) shows that both oven temperature and the interaction AC have an effect on the length of the bond, with no other factors having a statistically significant effect at the 0.05 alpha level. The main effects plot (figure 4.26) shows that the highest bond lengths are achieved with the highest setting for oven temperature, highest reheat time and lowest cooling temperature.

Figure 4.26 Main effects plot for bond length

The high level factors have the opposite effect on bond length as they do on sample tensile strength. This confirms the previous research conducted which suggests that annealing or reheating has a positive effect on bond length (while decreasing bond strength) (Graybill, 2010). However, as the P-value for reheat time is above the significance threshold of 0.05, it cannot be said that the null hypothesis is disproven.

Similar to the interaction plot for tensile strength, the interaction plot for bond length (figure 4.27) shows an interaction of AC (oven temp*part cooling temp). In the case of the bond length response though, intersection AC is statistically significant, whereas it was merely observed with no statistical significance for tensile strength. The largest bond length is achieved when the part is cooled to 100°C from an oven temp of 170°C.

Figure 4.27 Interaction plots for bond length

The normal plot of the standardized effects (figure 4.28) shows that all of the factors have a positive effect on bond length at the high levels, with only factor A (oven temp) and interaction AC being significant.

Figure 4.28 Normal plot of the standardized effects for bond length

Figure 4.29 Bar graph showing means of bond length

4.7.3.3 Effects of factors on Young's Modulus

From the ANOVA results for Young's modulus (figure 4.30) it is shown that the factors have no significant effect on the Young's modulus response. The R-sq value shows that 37.01% of the variance can be accounted for with this model. This is too low to use this particular regression model for making accurate predictions of bond length. The residual plots (figure 4.31) confirm that the criteria for ANOVA are satisfied for Young's modulus.

Analysis of Variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Oven Temp	1	23.144	23.1444	3.96	0.064
Part Cooling Temp	1	18.511	18.5111	3.16	0.094
Reheat Time	1	1.059	1.0586	0.18	0.676
Oven Temp*Part Cooling Temp	1	0.774	0.7738	0.13	0.721
Oven Temp*Reheat Time	1	0.866	0.8664	0.15	0.705
Part Cooling Temp*Reheat Time	1	10.031	10.0310	1.71	0.209
Oven Temp*Part Cooling Temp*Reheat Time	1	0.619	0.6195	0.11	0.749
Error	16	93.628	5.8517		
Total	23	148.633			

Model Summary			
S	R-sq	R-sq(adj)	R-sq(pred)
2.41904	37.01%	9.45%	0.00%

Figure 4.30 Minitab ANOVA results for Young's modulus

Figure 4.31 Residual plots for Young's modulus

The Pareto chart (figure 4.32) shows no significant effect of the factors on the response. The main effects plot (figure 4.33) shows that parts printed at higher temperature, the higher reheat time or highest cooling temperature all had higher mean responses compared to if the factors had been at the lower setting.

Figure 4.32 Pareto chart of standardized effects for Young's modulus

Figure 4.33 Main effects plot for Young's modulus

Figure 4.34 Interaction plots for Young's modulus

The interaction plot (figure 4.34) shows no interactions between any of the factors for Young's Modulus, while the normal plot for standardized effects (figure 4.35) shows no significant effect on the response.

Figure 4.35 Normal plot of standard effects for Young's modulus

Despite their being no statistically significant correlation between the factors and the responses, the means of the Young's modulus values per sample show that all of the treatments have had some observable effect on the response.

The bar graph showing the means of the modulus values (figure 4.36) show that every treatment combination has altered the young's modulus compared to the baseline values for untreated specimens. The graph shows that the treatments may have caused the elastic modulus to exceed the baseline values, suggesting that the treatments cause the specimens to become less ductile.

Figure 4.36 Bar graph of means of Young's modulus

The baseline for the untreated specimens was found to be 1.308 GPa for samples printed at 170°C and 1.584 GPa for those printed at 160°C.

4.7.3.4 Effects of factors on Maximum Strain

The ANOVA table (figure 4.37) shows that oven temperature has a P-Value of 0.002, meaning that this factor has a significant influence on the response. All other factors have no significant response on the maximum strain of the samples. The residual plots for strain (figure 4.38) show that assumptions for ANOVA are valid.

Analysis of Variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Oven Temp	1	2.20220	2.20220	14.22	0.002
Part Cooling Temp	1	0.47884	0.47884	3.09	0.098
Reheat Time	1	0.01260	0.01260	0.08	0.779
Oven Temp*Part Cooling Temp	1	0.00000	0.00000	0.00	0.996
Oven Temp*Reheat Time	1	0.10534	0.10534	0.68	0.422
Part Cooling Temp*Reheat Time	1	0.37750	0.37750	2.44	0.138
Oven Temp*Part Cooling Temp*Reheat Time	1	0.03154	0.03154	0.20	0.658
Error	16	2.47813	0.15488		
Total	23	5.68616			

Model Summary			
S	R-sq	R-sq(adj)	R-sq(pred)
0.393552	56.42%	37.35%	1.94%

Figure 4.37 Minitab ANOVA results for strain

Figure 4.38 Residual plots for strain

Figure 4.39 Pareto chart of standardized effects for strain

The Pareto chart (figure 4.39) confirms that only oven temperature has an effect on maximum strain, and the main effects chart (figure 4.40) shows that the elevated oven temperatures have a positive effect on the response.

Figure 4.40 Main effects plot for strain

The interaction plot (figure 4.41) shows a minor, statistically insignificant interaction between oven temperature and reheat time. The normal plot of effects (figure 4.42) shows that oven temperature has a significant positive effect on the strain.

Figure 4.41 Interaction plot for strain

Figure 4.42 Normal plot of standardized effects for strain

4.7.4 Optimal Responses

The goal of this experiment is to show the optimal combination of conditions that have the least adverse effect on the responses.

As bond length does not specifically affect the sample in terms of functionality, the two responses to be optimised are the sample strength and the modulus of elasticity. When embedding hardware, it is desirable to retain as much of the part strength as possible, as well as maintaining the elasticity of the sample.

The Minitab response optimiser can be used to determine the best responses by manipulating the end points of the sample space to yield the optimum response (Minitab, 2017).

By setting the Minitab response optimiser to maximize strength while minimising Young's modulus, the optimisation plot (figure 4.43) reveals that the best combination of factors conforming to those requirements are:

Oven temp = 170°C

Reheat time=2.05 minutes

Part cooling temp = 100°C

The D term on the plot represents the composite desirability and shows how well the optimiser achieves the required goals (on a scale of 0 to 1, with 1 being most desirable). It is shown that the most optimal combination has a desirability rating of 0.7877. This is because both Young's modulus and strength decrease when the reheat time increases, and so the trade-off affects the strength negatively more than its positive effect on elasticity.

Figure 4.43 Optimization plot

Response Optimization: Youngs Modulus, Strength						
Parameters						
Response	Goal	Lower	Target	Upper	Weight	Importance
Youngs Modulus	Minimum		13.0095	24.7241	1	1
Strength	Maximum	18.99	38.4200		1	1
Solution						
	Oven Temp	Reheat Time	Part Cooling Temp	Youngs Modulus Fit	Strength Fit	Composite Desirability
Solution 1	170	2.05	100	15.8325	34.8733	0.787699
Multiple Response Prediction						
Variable	Setting					
Oven Temp	170					
Reheat Time	2.05					
Part Cooling Temp	100					
Response	Fit	SE Fit	95% CI		95% PI	
Youngs Modulus	15.83	1.40	(12.87, 18.79)		(9.91, 21.75)	
Strength	34.87	2.47	(29.64, 40.10)		(24.41, 45.33)	

Figure 4.44 Optimization results from Minitab

The standard error of the fits (SE Fit) shows an estimated variation in the mean response for a specified set of predictor values and factor levels, and provides a confidence interval

for the prediction. In this case the confidence interval for both Young's modulus and tensile strength provides a very large range of values where a prediction may fall. This is due to the small R-sq values of the regression model (figure 4.44).

4.8 Conclusion

From the analysis it is demonstrated that the factors and interactions shown (table 4.6) have a statistically significant effect on the corresponding responses:

Table 4.6 Factors of significant effect

Factor	Response	P-Value
Oven Temp	Strength	0.03
Oven Temp	Bond Length	0.004
Oven Temp * Cooling Temp	Bond Length	0.018
Oven Temp	Strain	0.002

Varying the parameters within the sample space have shown that there is no statistically significant effect on the elastic modulus of the samples: only the bond length, strength and strain are affected. Only the oven temperature, the cooling temperature and the interaction of those two factors have statistically significant effects on those responses.

Upon examination of the cube plot for strength (figure 4.45), it is shown that the highest strength samples have a mean strength of 36.27 MPa and result from a combination of 170°C oven temp, a reheat time of 2.05 minutes and a part cooling temperature of 80°C (although the reheat time has no statistically significant effect on bond strength).

Conversely the weakest samples (23.8 MPa) result from a combination of 160°C oven temp, 10.05 minute reheat time and 80°C cooling temp.

Conclusively, higher strength samples are achieved from the highest temperature oven setting of 170°C and a cooling temperature of 80°C.

The complete table of cooling and reheating / steady state reheat times can be found in Appendix D. There is a general trend that shows the highest strengths come from a high oven temperature of 170°C, and that reheating the foundation part after printing is resumed can potentially have a weakening effect on the bond layer.

Figure 4.46 Cube plot for strength response

This experiment has shown that the effects of the thermal history on the bond layer cannot be reversed with the specified experiment parameters. The effects can only be minimised. However, it has been shown in research (Fischer & Schoppner, 2017) that the application of chloroform vapour can increase the tensile strength of ULTEM (figure 4.46). The optimum experiment parameters shown in this experiment should be used in combination with the chloroform vapour treatment. A summary of this process can be found in Appendix E.

Figure 4.45 Effect of chloroform on strength treatment (Fischer & Schoppner, 2017)

5. Chapter 5: Conclusions

5.1 Conclusions

This research started as a project to see if it was possible to print a functional drone in a single manufacturing stage in an aerospace grade thermoplastic at high temperature.

The results of the project have shown that it is indeed possible, and highlights the limitations of such a process, and suggests a possible path forwards if this type of hybrid printing/assembly process is to be pursued in the future.

Figure 5.1 Completed drone, finished in blue polyurethane paint

As the literature review has shown, there are a number of different initiatives underway to develop printing of electronic systems, ranging from direct extrusion of conductive tracks, to pick and place systems combined with a printing phase. It is very likely that research will continue in these areas, and there will be no single “correct” way for achieving these manufacturing goals, simply because there are so many goals and so many methods of achieving them. It is quite possible that parallel methods will be developed and will be utilized according to the needs of the manufactured end product.

Although it has been shown that researchers have had some success with more complicated electronic components such as transistors, 3D printing of high density components such as those found on computer and smart phone chips will not be forthcoming in the near future. For this reason, there is still value in the pursuit of embedding complicated electronic systems within 3D printed FDM substrates, at least until the point where additive manufacturing can print transistors at nanometre scales.

This project has demonstrated the feasibility of embedding multiple systems within an aerospace-grade thermoplastic, at high temperature. This could have potential applications in aerospace, or even spacecraft component design, where the mass budget could be reduced by directly embedding sensors within a structure rather than using additional hardware brackets and fittings.

Regarding the process, however, it has been shown that there are limitations to using the method used in this thesis, namely the reduction of strength in the z-axis direction, caused by the cooling of the base part when the printer door is opened to embed the parts.

This leaves two possible outcomes for hybrid printing and assembly processes for high temperature materials:

The first outcome is to minimise the length of time for which the printer door is opened, thus reducing the cooling and manual handling of the part.

The second outcome is to avoid opening the printer door, and to develop high temperature printers with a pick and place system installed inside the heated chamber.

Although the first, manual solution is acceptable for small research projects, it lacks the control and predictability required to make products of a consistently high quality. There is too much capacity for human error.

The optimal solution, therefore, is that pick and place systems should be installed inside high temperature FDM printers, especially if manufacturing larger volumes of parts that require consistent quality.

5.2 Original contributions

The main contributions of this project are:

- Demonstration of the printing of a functional quadcopter with embedded electronics in one step, using high temperature ULTEM 9085 thermoplastic. This project marks the first publically documented occurrence of embedded complex electronics within an ULTEM 9085 structure (NTU Singapore, 2016).
- Determine the optimal combination of factors that will reduce the loss of strength between bond layers.
- Highlight the best methodology for designing small-scale snap-fit clips out of two different methods, and introduce the *zone of manufacturability*, which considers the dimensions of the printer contour paths and a given strain value.

5.3 Recommendations for future work

To gain a complete understanding of the weakening of the bond layer and provide a more accurate model for predicting the bond strength, it would be recommended to design a 3 level factorial design with a higher quantity of samples. This would allow a non-linear model to be determined and would potentially reduce the experimental error and allow smaller deviations from the means to be detected.

Unfortunately the Fortus 450mc only permits 2 levels of oven temperature settings, so with the Fortus only a mixed level factorial would be possible with that apparatus.

Therefore, an ideal bond strength experiment would involve a custom built printer with at least 3 oven temperature settings.

Researchers at NASA Langley have modified a Lulzbot 3D printer with a higher temperature hot end, and have used halogen lamps fitted inside the printer chamber as an infrared heat source to maintain heat in the chamber. This modified printer has been proven capable to print ULTEM 9085, and seems to be a cost-effective solution allowing more customisation in printing parameters compared to the Fortus 450mc (Gardner, Stelter, Yashin, & Siochi, 2016).

Regarding future applications of a high-temperature drone, the drone in this project has proven that the electronics are capable of surviving temperatures far in excess of what they were designed for. The most prominent single point of failure for a drone of this type is the lithium polymer battery pack. At the present, lithium ion battery packs are limited to a maximum temperature of around 130°C. Above this temperature, the polymer layers inside the battery begin to break down and can result in thermal runaway, venting, fire and explosion (McKissock, Loyselle, & Vogel, 2009). Realistically though, most lithium polymer cells are rated for much lower operating temperatures, as decomposition of the solid electrolyte interphase can begin at around 85°C (Yang, Amiruddin, Hyun, Sun, & Prakash, 2006).

Future advances in battery technology could in principle enable the construction of a drone, manufactured in a high temperature process with high-strength aerospace-grade plastics, capable of operating temperatures in excess of 130°C and below the printer temperature of 170°C. This could provide useful for applications such as volcanology or firefighting.

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Appendix A

Table 14 ULTEM 9085 Datasheet (Stratasys, 2016)

Mechanical Property	Test Method	XZ Orientation	ZX Orientation
Tensile Strength, Yield (Type 1, 0.125", 0.2"/min)	ASTM D638	47 MPa	33 MPa
Tensile Strength, Ultimate (Type 1, 0.125", 0.2"/min)	ASTM D638	69 MPa	42 MPa
Tensile Modulus (Type 1, 0.125", 0.2"/min)	ASTM D638	2,150 MPa	2,270 MPa
Tensile Elongation at Break (Type 1, 0.125", 0.2"/min)	ASTM D638	5.80%	2.20%
Tensile Elongation at Yield (Type 1, 0.125", 0.2"/min)	ASTM D638	2.20%	1.70%
Flexural Strength (Method 1, 0.05"/min)	ASTM D790	112 MPa	68 MPa
Flexural Modulus (Method 1, 0.05"/min)	ASTM D790	2,300 MPa	2,050 MPa
Flexural Strain at Break (Method 1, 0.05"/min)	ASTM D790	No break	3.70%
IZOD IMPact, notched (Method A, 23°C)	ASTM D256	120 J/m	48 J/m
IZOD IMPact, un-notched (Method A, 23°C)	ASTM D256	781 J/m	172 J/m
Compressive Strength, Yield (Method 1, 0.05"/min)	ASTM D695	100 MPa	87 MPa
Compressive Strength, Ultimate (Method 1, 0.05"/min)	ASTM D695	181 MPa	90 MPa
Compressive Modulus (Method 1, 0.05"/min)	ASTM D695	7,012 MPa	1,731 MPa
Thermal Property	Test Method		
Heat Deflection (HDT) @ 264 psi, 0.125" unannealed	ASTM D648	153°C	
Glass Transition Temperature (Tg)	DSC (SSYS)	186°C	
Coefficient of Thermal Expansion	ASTM E831	65.27 $\mu\text{m}/(\text{m}\cdot^{\circ}\text{C})$	
Melting Point	-----	Not Applicable	
Electrical Property	Test Method	Value Range	
Volume Resistivity	ASTM D257	4.9 x10 ¹⁵ - 8.2x10 ¹⁵ ohm-cm	
Dielectric Constant	ASTM D150-98	3 - 3.2	
Dissipation Factor	ASTM D150-98	.0026 - .0027	
Other Properties	Test Method	Value	
Specific Gravity	ASTM D792	1.34	
Rockwell Hardness	ASTM D785	---	
Flame Classification	UL94	V-0 (1.5 mm, 3 mm)	
Oxygen Index	ASTM D2863	0.49	
OSU Total Heat Release (2 min test, .060" thick)	FAR 25.853	16 kW min/m ²	
UL File Number	-----	E345258	
Fungus Resistance (Method 508.6)	MIL-STD-810G	Passed	
Heat Release	14 CFR/FAR 25.853	Passed (0.060" thick)	
NBS Smoke Density (flaming)	ASTM F814/E662	Passed (0.060" thick)	

NBS Smoke Density (non-flaming)	ASTM F814/E662	Passed (0.060" thick)	
Outgassing			
Total Mass Loss (TML)	ASTM E595	0.41% (1.00% max)	
Collected Volatile Condensable Material (CVCM)	ASTM E595	-0.1% (0.10% max)	
Water Vapor Recovered (WVR)	ASTM E595	-0.37% (report)	
Burn Testing			
Horizontal Burn (15 sec)	14 CFR/FAR 25.853	Passed (0.060" thick)	
Vertical Burn (60 sec)	14 CFR/FAR 25.853	Passed (0.060" thick)	
Vertical Burn (12 sec)	14 CFR/FAR 25.853	Passed (0.060" thick)	
45° Ignition	14 CFR/FAR 25.853	Passed (0.060" thick)	

Appendix B

Table 15 Non-randomized run table

RunOrder	Oven Temp	Reheat Time	Part Cooling Temp	Bond Length	Stress	Strain	Youngs Modulus	Sample ID
1	160	2.05	80	506.625	28.32	1.54	18.39	6b(a)
2	160	2.05	100	465.157	26.96	1.43	18.85	5(a)
3	160	10.05	80	570.955	18.99	1.16	16.37	8b(a)
4	160	10.05	100	527.740	27.32	2.10	13.01	7(a)
5	170	2.05	80	496.730	37.47	2.13	17.59	3b(a)
6	170	2.05	100	500.960	38.42	2.34	16.42	1(a)
7	170	10.05	80	520.135	31.93	1.78	17.94	4b(a)
8	170	10.05	100	540.925	22.64	1.24	18.26	2(a)
9	160	2.05	80	496.875	22.83	1.23	18.56	6b(b)
10	160	2.05	100	471.020	29.71	1.58	18.80	5(b)
11	160	10.05	80	505.955	28.68	1.16	24.72	8b(b)
12	160	10.05	100	456.675	31.94	1.58	20.22	7(b)
13	170	2.05	80	543.230	36.53	2.18	16.76	3b(b)
14	170	2.05	100	523.720	28.04	1.63	17.20	1(b)
15	170	10.05	80	493.345	35.27	1.90	18.56	4b(b)
16	170	10.05	100	618.150	35.90	2.74	13.10	2(b)
17	160	2.05	80	488.220	31.11	1.64	18.97	6b(c)
18	160	2.05	100	479.295	24.21	1.28	18.91	5(c)
19	160	10.05	80	538.455	23.83	1.38	17.27	8b(c)
20	160	10.05	100	492.207	29.63	1.84	16.10	7(c)
21	170	2.05	80	563.120	34.82	2.10	16.58	3b(c)
22	170	2.05	100	587.800	38.16	2.75	13.88	1(c)
23	170	10.05	80	546.925	28.59	1.66	17.22	4b(c)
24	170	10.05	100	579.537	35.90	2.74	13.10	2(c)

Appendix C

Table 16 Thermal profile information for experimental runs

Std Order	Run Order	Oven Temp (°C)	Reheat Time (m)	Part Cooling Temp (°C)	Cooling time (m)	Reheat time (m)	ID
20	1	160	10.05	100	3:22	6:16	7(c)
15	2	170	10.05	80	7:00	11:12	4b(b)
4	3	160	10.05	100	3:22	6:16	7(a)
16	4	170	10.05	100	4:02	7:57	2(b)
8	5	170	10.05	100	4:02	7:57	2(a)
2	6	160	2.05	100	3:08	5:50	5(a)
13	7	170	2.05	80	7:00	11:10	3b(b)
6	8	170	2.05	100	3:50	7:01	1(a)
17	9	160	2.05	80	6:18	8:50	6b(c)
9	10	160	2.05	80	6:18	8:50	6b(b)
3	11	160	10.05	80	6:16	9:02	8b(a)
18	12	160	2.05	100	3:08	5:50	5(c)
21	13	170	2.05	80	7:00	11:10	3b(c)
11	14	160	10.05	80	6:16	9:02	8b(b)
10	15	160	2.05	100	3:08	5:50	5(b)
1	16	160	2.05	80	6:18	8:50	6b(a)
12	17	160	10.05	100	3:22	6:16	7(b)
23	18	170	10.05	80	7:00	11:12	4b(c)
22	19	170	2.05	100	3:50	7:01	1(c)
7	20	170	10.05	80	7:00	11:12	4b(a)
14	21	170	2.05	100	3:50	7:01	1(b)
19	22	160	10.05	80	6:16	9:02	8b(c)
24	23	170	10.05	100	4:02	7:57	2(c)
5	24	170	2.05	80	7:00	11:10	3b(a)

Printer heating and cooling profile for sample group 1 (above)

The line graph above shows the part temperature in green as measured by the IR thermometer. The blue line represents the temperature as logged by the printer control panel display. Note that there is a lag between the part temperature and the printer chamber temperature. The printer chamber lost heat at a faster rate than the part (this is confirmed in the thermal images shown in chapter 4.6). The graph above represents readings taken from sample group 1, which had a print chamber temperature of 170°C, a part cooling temperature of 100°C and a steady state reheat time of 2 minutes 5 seconds. During cooling the printer chamber reached a temperature of 89°C.

All experiment runs exhibited this same lag between the part temperature and the oven temperature.

Appendix D

Flow chart of embedding instructions

Appendix E

Due to the nature of FDM type 3D printing, there can be a stepped effect on the finished product, and the severity of this effect depends on the angle of the item being printed. This can produce a rough finish on the surface of the printed part.

It has been demonstrated that the stepped effect can be alleviated on plastic parts by the application of a solvent in a liquid or vaporous form. The solvent is applied to the part and it melts the steps on the surface of the part, resulting in a smooth finish similar to that found on injection molded parts.

Different chemical solvents can have different effects on plastics, and in some cases, a solvent that may work on one type of thermoplastic may not have an effect on another type.

The online 3D printing community prefer to use chemicals such as acetone on items printed with PLA and ABS, due to availability and also due to low toxicity. However, acetone has no effect on ULTEM 9085. To perform this chemical smoothing on ULTEM 9085, chloroform vapor must be used.

It has been shown that application of chemical smoothing can not only enhance the physical appearance of the printed part but it can also improve the tensile strength of parts printed in ULTEM 9085 (Fischer & Schoppner, 2017).

The following procedure describes the process of applying chloroform vapor to ULTEM 9085 tensile test coupons:

- 1) The ASTM D638 test coupons were printed with a T16 tip on the Fortus 400mc with a layer thickness of 0.254mm in each of the three build orientations.
- 2) A wide, flat glass vessel was filled with liquid chloroform up to a height of 15mm.

- 3) The tensile coupons were placed in a holder within the vessel so that they were positioned above and parallel to the fluid surface.
- 4) The vessel was sealed with a lid.
- 5) The vessel is placed in a vented area, at room temperature for 2 hours.
- 6) For uniformity of application, the specimens are rotated 180 degrees after 1 hour.

It was noted in the research that after approximately 150 minutes of exposure to the vapor in the vessel that the surface began to deteriorate and mechanical properties would be affected after this time (hence why 120 minutes was selected for the main experiments).

For the samples printed in the X and Y orientation, it was shown that there was no significant change to tensile strength after the chemical treatment had been applied.

For samples printed in the Z orientation, it was demonstrated that the tensile strength was increased by approximately 16%, while the elongation at break was increased by approximately 24%. The fatigue tests of the chemically treated specimens showed no significant increase in lifetime compared to untreated specimens (Fischer & Schoppner, 2017).

This research indicates that chemical treatment of chloroform can be used to increase the strength of ULTEM 9085 test coupons. Further research in this area would be needed to determine if this chemical treatment can also increase the strength of printed objects that have been paused and allowed to cool while hardware is embedded.

Appendix F

The following figures show the dimensions of the embedded hardware housings for the discrete electronic components. The fittings are printed prior to the main printing job and are dual purpose: they provide a good fit for irregular shaped electronic hardware as well as protect the electronics from the heat of the freshly extruded filament. The contact faces have been designed to provide the smallest contact area possible to minimize heat conductivity from the main printed body

Flight controller housing dimensions

Bottom faces of flight controller housing- the plate is 2mm thick (above)

Close up of contact points for flight controller- both inner and outer diameters are dimensioned (above)

The 4x rotor arms each have a thickness of 2mm throughout the entire section. The ESCs are embedded within (above)

The receiver housing is the last part to be embedded due to the low survivability of the component. Heat is transferred from the main body via the 2 rails at the bottom, and the topmost surface protects the component from the heat of the freshly extruded filament (above)

Appendix G

All of the test prints and the final print were printed with the following parameters:

Printer: Fortus 400 mc

Material: ULTEM 9085

Support material: BASS (Breakaway Support Structure)

Chamber Temperature: 170°C

Slice height: 0.254 mm

Extruder tip: T16

All prints were performed in the orientation shown below, with the bottom of the model being parallel to the printer build platform:

Print orientation of quadcopter

The following images show the toolpaths and contours at each of the three pauses where the hardware was embedded:

1st pause (above)

2nd pause (above)

3rd and final pause (above)