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EMBEDDING ELECTRONICS IN PRINTING ULTEM 9085 QUADCOPTER

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ABSTRACT: This paper demonstrates the techniques and processes involved for embedding electronics within a monolithic 3D printed structure (a quadcopter frame), using a Fortus mc450 FDM machine and the ULTEM 9085 thermoplastic. ULTEM 9085 can only be printed in a high temperature environment, and this paper shows the hurdles and solutions associated with embedding electronics in this environment.

KEYWORDS: FDM, ULTEM 9085, Quadcopter, Drone, Additive Manufacturing

INTRODUCTION

There are a lot of benefits, particularly in aerospace and automotive engineering applications, to embedding electronic systems within structural bodies.

First and foremost is the benefit of weight reduction. Typically, electronic hardware must be fitted into some form of protective casing before being mounted onto a bracket, and then onto the airframe section (or into a car) where the hardware can potentially become exposed to variations in pressure, temperature and moisture. By using additive manufacturing to embed the electronics into structural elements, the need for protective casing and brackets can be alleviated, reducing weight and cost while adding protection from the elements.

ULTEM 9085 is an engineering thermoplastic used widely in the aerospace industry due to its high tensile and specific strengths relative to other 3D printed thermoplastics (see Figures 1 and 2). Additionally, ULTEM 9085 has been certified for use in commercial aviation and spaceflight applications, due to its low toxicity and low outgassing properties.

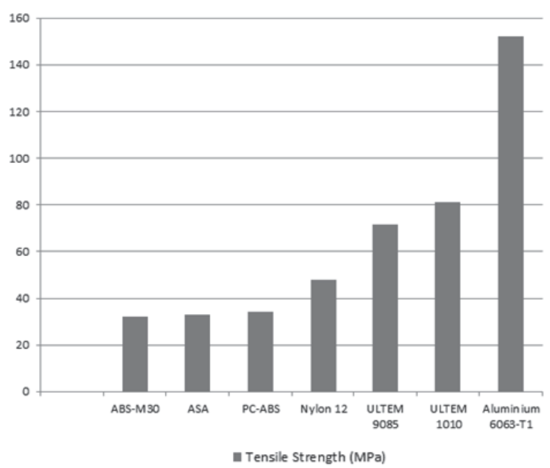

Figure 1 Tensile Strength of various 3D printed plastics compared to Aluminium 6063-T1

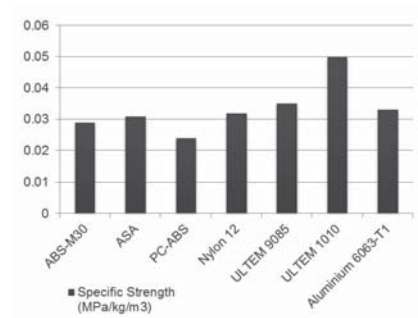

Figure 2 Specific strength of various 3D printed plastics compared to Al-6063-T1

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REDUCING MANUFACTURING STEPS

Fly out of the printer

In addition to the weight saving benefits, an additional goal of this project was to demonstrate that the whole production process for complex products could be shortened by alleviating post-production stages, allowing for a finished product with embedded hardware could be ready for use as soon as it had finished printing. In short, it was the intention to demonstrate that a 3D printed quadcopter could fly straight out of the printer.

In principle, adding mechanical, static hardware during a print is not complicated. According to Stratasys best practices, a hardware piece (for example, a metal washer) can be embedded by first designing a cavity into the CAD model, allowing some clearance for shrinkage as the 3D printed part cools. Then, a layer of acrylic spray paint is applied to the top side of the embedded part to allow adhesion from the extruded thermoplastic in the printer. The pause can be preprogrammed in the print software- in this case, the Stratasys Insight software was used, and during the print job the process will stop allowing for the hardware to be manually installed before the printing recommences. **Stratasys (2014)**

However, the addition of electronic COTS hardware adds a whole new dimension of complexity to a project such as this one, largely due to the high temperatures within the 3D printer when it is extruding the ULTEM 9085 material. Additionally, to reduce post-processing after the print job was complete, it was decided to design the internal geometry to be self-supporting, and thus eliminating the need for support structure, which would require mechanical removal or submersion in a liquid medium to dissolve the soluble supports, which is not ideal for electronic systems.

In order to facilitate a flat geometry to print over the electronics, and also to protect the electronics from the temperature of the freshly extruded filament (330°C-360°C), it was decided to print several hardware adapters (see Figure 3) into which the electronics would be placed before printing over them.

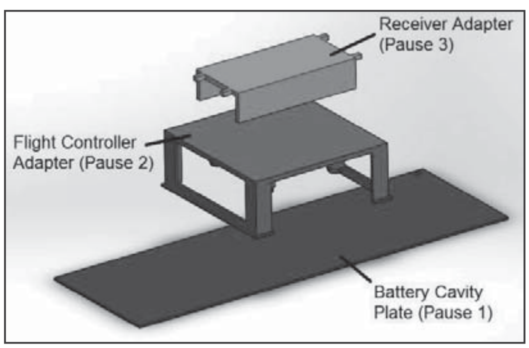

Figure 1 Protective adapters manufactured from ULTEM 9085

The temperatures for printing with ULTEM 9085 from a Fortus 3D printer are typically as follows **Bagsik et al. (2010)**:

Build chamber =195°C	ULTEM 9085 glass transition temperature = 181°C
Extruding tip temperature is 380°C	Normal extrusion temperature 330°C-360°C

The quoted operating temperature range for COTS quadcopter components is in the range of 0°C-55°C, although operating temperature is not the same as storage temperature, or even the maximum temperature that the components can be exposed to. So given the unreliability of the published information on these components, it was decided that a more empirical approach was needed, in order to test the survivability of the components when subjected to the build chamber temperature.

Typically, ULTEM 9085 is printed with a build chamber temperature of 195°C, in excess of the glass transition temperature of the material. However, certain components in early tests burned out at a much higher rate at this elevated temperature, so the chamber temperature was lowered below the glass transition temperature of ULTEM 9085, down to 170°C. This still allowed the plastic to fuse to the preceding layers during printing, while minimized the effects of thermal warping.

The following electronic components are the bare minimum requirements needed to construct a quadcopter, and the table shows the survival times based on experimentation.

Component	Quantity	Description	Survival time in minutes (170°C)
Naze32 Flight Controller	1	Stability and control computer	>240
Drone Matters 20 Amp ESC	4	Speed controllers for motors	>240
Cobra CM2213/950 motor	4	Motors for propulsion	N/A
Zippy LiPoly 6200mAh battery	1	Power supply	N/A
Futaba R2008SB receiver	1	Radio controller receiver	35

Table 1. List of components and survivability

Limitations of hardware

Asides from the thermal limitations stated above, there are geometric aspects to consider when embedding electronics, which must be overcome via use of custom plastic adapters.

The distance between the extruder head to the part being manufactured is <5mm, inside a Fortus printer, and in order to achieve optimal adhesion (and avoid collision with hardware), the topmost layer of the part being printed must be completely flat.

For these reasons, both the motors and the battery could not be installed during the printing phase. The upper operating range for lithium batteries is in the region of 70°C -90°C, and some can even be operated up to 137°C before experiencing thermal runway, and explosion. **Tichy (2010).** Again, given the ambiguity in the hardware literature, it was decided not to risk exposing the battery to heat, especially as the upper limit is far below the build chamber temperature.

The motor, being magnetic, will lose its magnetism when subjected to temperatures above 80°C. Additionally, the raised motor spindle and casing protrudes 27mm above the printed layer, which would cause a collision with the extruder head (see Figure 4).

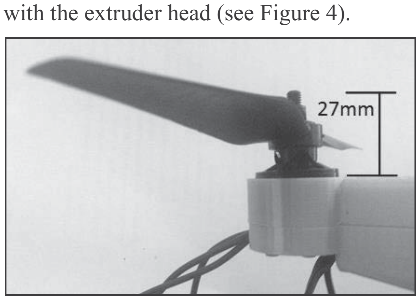

Figure 2 Distance of propeller/motor shaft above safe printing level

Given the varying survival time of the components, a strategy was developed to add the least heat resistant components at the top part of the drone, meaning that they were installed closer to the end of the print job, thus reducing exposure to the high temperature chamber. In this case, the item with the highest chance of failure was the Futaba R2008SB receiver, which had been shown to fail after 30 minutes at the chamber temperature. By installing this component last and designing the CAD file accordingly, it was ensured that the exposure to heat could be kept below the dangerous exposure time (it was only exposed to the printer for 20 minutes).

Thermal issues during hardware embedding

In order to embed the hardware mid-print, the Fortus machine must be set to pause, the gantry must be lowered, the vacuum must be eliminated, and the printer door must be opened in order for manual installation of the hardware into the structure.

Upon completion of the test prints, it was noted that the preceding layers had undergone thermal contraction during the period where the door was open, and the heat had escaped. This resulted in a clear join line where the printer had resumed over the installed hardware (see Figure 5).

It has been observed that this is not merely a cosmetic issue, but is a mechanical weakness in between bonded layers which allows the part to be separated with relative ease.

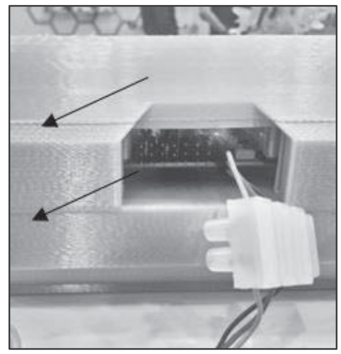

Figure 3 Distortion lines created by cooling during mid-print pause

Embedding Process

Three pauses were needed during the printing process, in order to embed the hardware and adapters. (See Figure 6 for placement of hardware adapters, and printer pause timings)

Pause 1 was made at 5 hours 11 minutes into the job, and allowed the battery adapter plate to be fitted.

Pause 2 was made at 9 hours 10 minutes into the job, enabling fitting of the pre-assembled flight controller and 4x ESCs. This was the most difficult task and required the printer door to be opened for an extended period of time, resulting in the shrinkage and weakening of the join at this layer.

Pause 3 was made at 13 hours 20 minutes into the job, and allowed the installation and wiring of the radio receiver.

20 minutes after the final pause and embedding of the receiver, the final layers were printed over the top of the receiver adapter and the print job was complete, totaling 13 hours and 40 minutes.

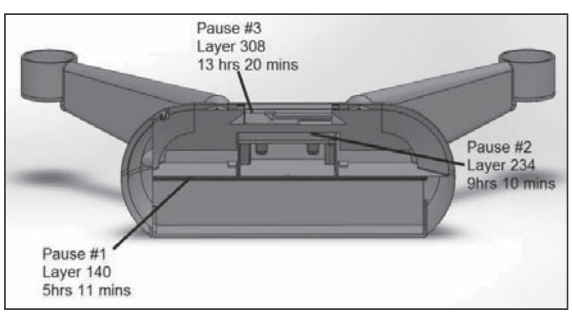

Figure 4 Cutaway drawing showing placement position and pause times for adapter installation

Final Outcome and Remarks

After many design iterations based on the various tests and observations, a working drone was printed complete with functioning flight hardware.

As mentioned previously, there was some remaining assembly work, namely the motors/propellers and battery installation.

The drone is functioning as expected, and the prototype has been deemed a successful project.

However, there is certainly room for improvement in the process of embedding electronic hardware, and it is conceivable that once these issues are sorted out, we could see the development of hybrid 3D Printer/Pick and Place machines, which will create both the structure and the hardware, with minimal need for human interaction.

However, to achieve this goal, the following points must be addressed:

- Heat proof electronics – COTS parts are not designed for such high temperature. Solder joints tend to contract during heating and cooling, and break free from PCBs, and also, standard PVC cable insulation is not sufficient for the task. Simply replacing the solder with a higher temperature solder, and the cables with silicon insulation can begin to address these issues.
- Thermal distortion- the weakening and visible lines caused during the cooling as the door is opened can be addressed by construction of a printer with a robotic arm inside. This will alleviate the need to open the door to install hardware, and eliminate the potential for injury to human operators.
- Thermal contraction around hardware. The electronic parts with the ULTEM adapters fit without issue, and there was no cracking around these areas. However, the ESCs were placed into the drone arms without adapters, and when the drone cooled, the printed casing shrunk around the hardware. This can be overcome by designing larger cavities to allow for shrinkage.

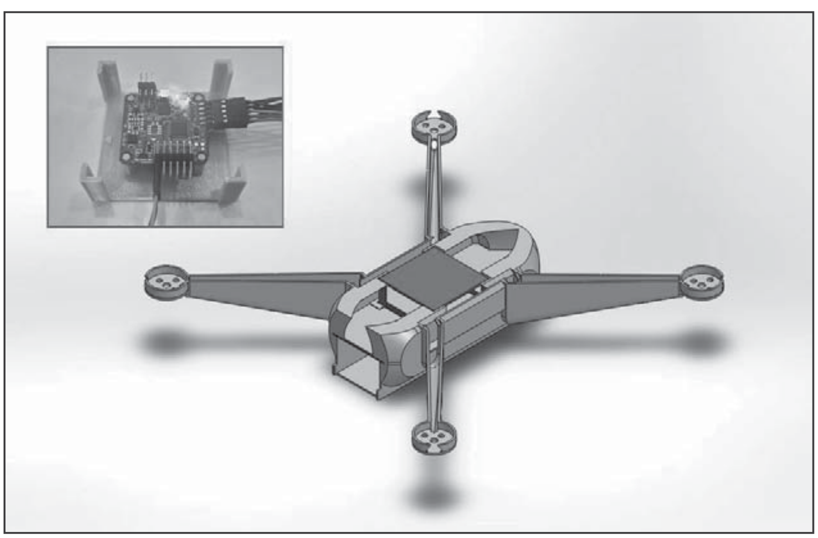

Figure 5 Flight controller adapter installation layer. In the top corner, the real life hardware is shown within the adapter.

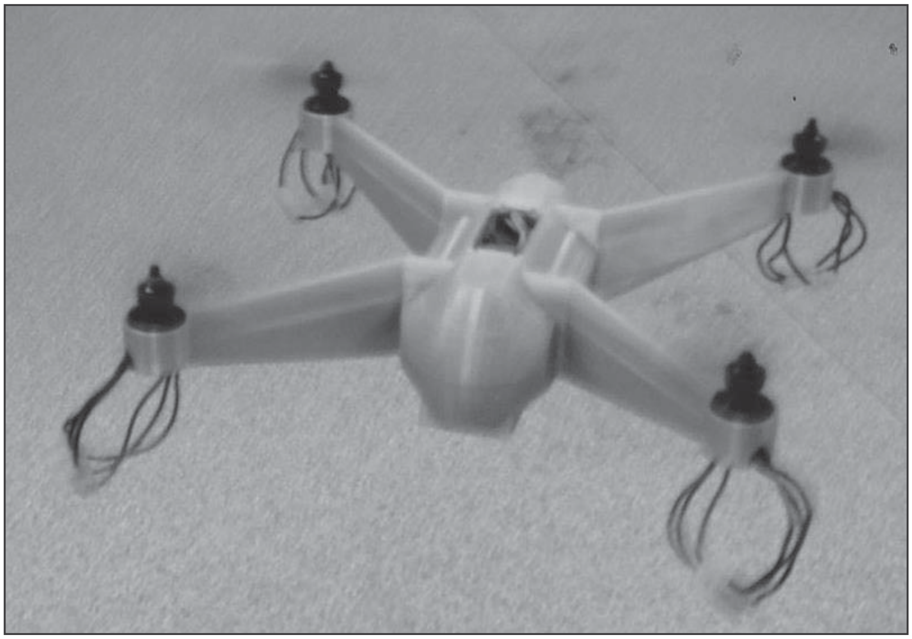

Figure 6 Prototype drone in flight

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