ULTEM 9085 Resin Quadcopter-Project

FLY OUT OF THE 3D PRINTER

Is it possible to design a drone with commercial off-the-shelf (COTS) electronic hardware that is embedded during the 3D printing process? Is it possible to manufacture a drone that could effectively be ready for flight as soon as it is 3D printed? These questions formed the basis of this project and led to an exploration of hybrid 3D printing and the benefits of embedded hardware.

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Conceived by Ido Eylon and Stanley Leung of Stratasys Asia, this paper demonstrates the techniques and processes involved in embedding electronics within a monolithic 3D printed structure, a quadcopter frame, using a Fortus 450mc™ FDM® 3D production system and ULTEM™ 9085 resin. ULTEM 9085 resin requires a high temperature environment, and this paper demonstrates the obstacles and solutions associated with embedding electronics in this environment.

3D PRINTED DRONES

3D printed drones are nothing new. There are many examples of drone airframes available on Thingiverse and GrabCAD. However, all of these examples are designed to be printed as a separate frame before the electronics are added.

During the early phase of this project, the plan was to use ABS or ASA. Approximately one month into the project, 3D printer manufacturer Voxel8 announced to the public they had designed a drone that was printed with hardware embedded mid-print, and featured printed conductive circuit tracks, a feature of the Voxel8 system. The Voxel8 drone was printed in PLA at room temperature. So we decided to up the ante. We chose to use ULTEM 9085 resin, thus making this the first drone with embedded electronics to be printed in a high temperature environment.

Figure 1 Receiver in the original hard case

Early research showed that COTS products are not designed for high temperature operations, with an average specified operating temperature in the region of 120°C. Solid state electronic components can survive much higher temperatures. When it comes to components containing magnets, fluids or batteries, that value drops to around 80-100°C.

We began a campaign of testing various components. After designing the general CAD model, and calculating when we should pause the printer for embedding the hardware, we began bake-tests of the various hardware components. We produced a bill of materials (BOM) of suitable hardware candidates, all of which demonstrated the ability to survive the printing process (with the exception of batteries and motors, which must be

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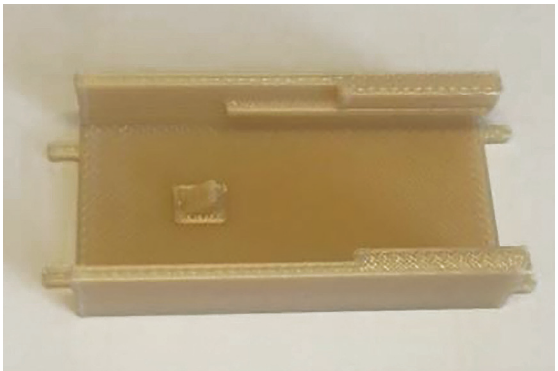

Figure 2 Custom ULTEM 9085 resin adapter. Receiver PCB was placed in here.

added post printing in the case of ULTEM 9085 resin print temperatures).

ADAPTERS

Due to the uneven shape of the flight hardware electronics, which feature the raised PCB components on one side and solder pins on the other, We decided to pre-print adapters for the hardware using ULTEM 9085 resin. This would serve three purposes:

1. Create a flat surface to print over, and prevent collisions with the components and extruder.
2. Protect the components from the heat of the extruded material.
3. Serve as a location jig to ensure components stay fixed in the drone body during printing.

Additionally, because the hardware would effectively become sealed inside the unit and prevent access for support material removal, the drone was designed to have zero internal support material. In the case of the battery cavity, a flat plate was pre-printed that would be installed during the first pause to create a cavity to install the battery.

FUTABA R300SB RECEIVER ADAPTER

The Futaba R300sb receiver adapter was the most susceptible to heat damage, having a survival time of no more than 20 minutes within the printer. For this reason, it was placed high up in the build (z-axis) and was printed over last, thus reducing time in the printer.

1. The first step was to remove its hard plastic case to prevent melting. Removal was easy, as it is fastened with clips only.
2. The default wiring harness is manufactured from PVC cables and ABS connectors. These needed to be replaced (see section on wiring modifications).
3. To successfully print over this component, the adapter had to be manufactured from ULTEM

9085 resin. This was necessary to protect the component from extrusion heat, provide a mating surface for installation and provide a flat surface to print over. The circuit was slotted into the adapter.

NAZE32 ACRO FLIGHT CONTROLLER ADAPTER

A variety of budget flight controllers were tested, and the Naze32 Acro showed the highest resistance to heat, and it offered the lowest volume. There are several variants of the Naze32 board, ranging from the Acro version up to the full version. The full version contains sensors such as a barometer and magnetometers.

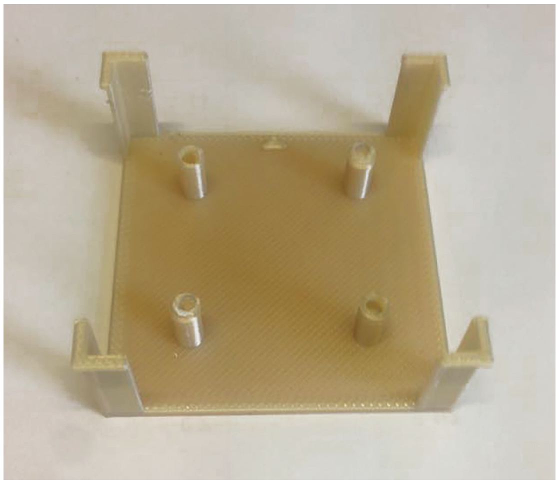

Figure 3 ULTEM 9085 resin Flight Controller adapter

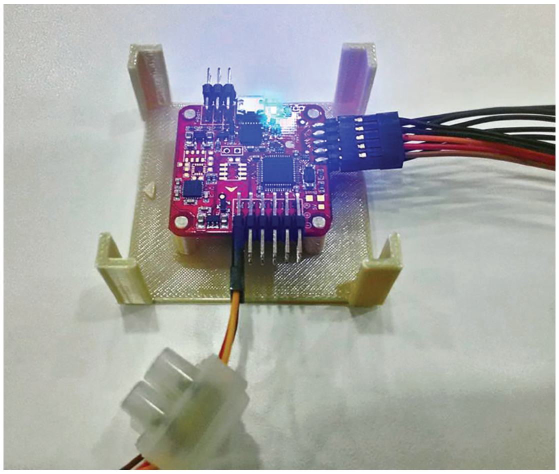

Figure 4 Naze32 installed in the adapter

There was some uncertainty as to whether the barometer and magnetometer would survive the printing process, so we opted for the Acro version. This means that there was reduced risk from single point failure of the barometer affecting the entire board. But it also means we would not benefit from the altitude hold and position hold functions for the drone. By opting for the Acro board, we would have to fly manually.

PRINTING THE DRONE

The total printing time for the drone was just under 14 hours total. During that time, there were three pauses in which the printer door was opened and the hardware was positioned within the structure. This is shown in figure 6.

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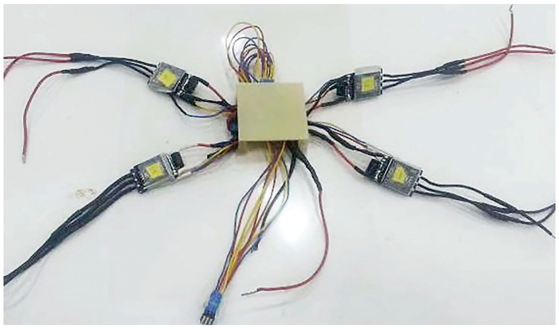

Figure 5 The center flight controller, four ESCs ready to be installed into drone arms, and the receiver cable (and power leads) visible at the bottom

Pause 1 occurred at layer #140 to embed the pre-printed ULTEM 9085 resin battery cavity plate.

Pause 2 occurred at layer #232. This was the most complicated part, as the pre-assembled flight controller, flight controller adapter and ESCs were embedded.

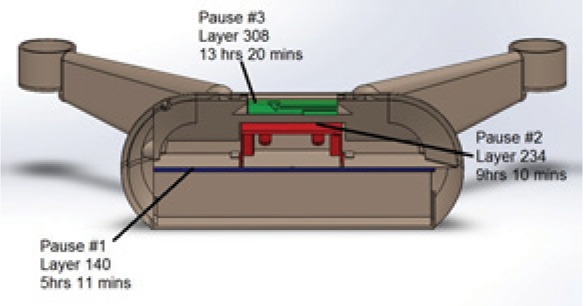

Figure 6 Cutaway view shows the location of hardware adapters.

Pause 3 occurred at layer #308 to embed the receiver and receiver adapter. During this pause, the receiver wire was connected to the flight controller which was embedded during the second pause. This was also very tricky as it required nimble fingers operating in a very hot environment.

During the installation of hardware, all components had to be totally flush with the layer to be printed on, in order to avoid collisions with the extruder head. Figure 7 shows an early test print, which was aborted due to thermal stresses affecting the print job, but shows how the assembly was installed during the second pause.

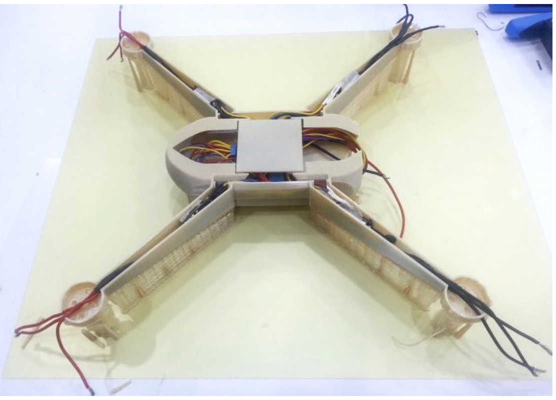

Figure 7 Aborted test print which shows embedding of main assembly.

To prevent the support from cracking and misalignment of the drone, the following preventative measures were carried out:

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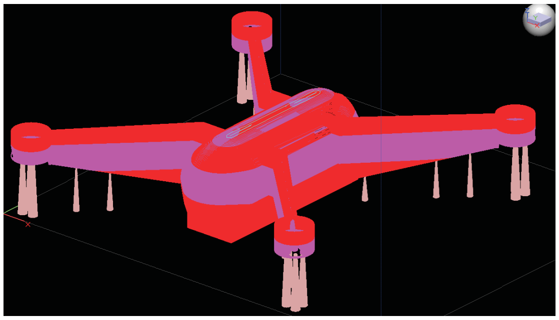

Figure 8 In addition to the auto-generated external support structure, additional anchor columns were added.

1. Anchor columns were added to help fix the drone to the print bed (figure 8).
2. The door was not open for more than five minutes at a time.
3. Hardware was installed very gently, so as not to disturb the position of the drone.

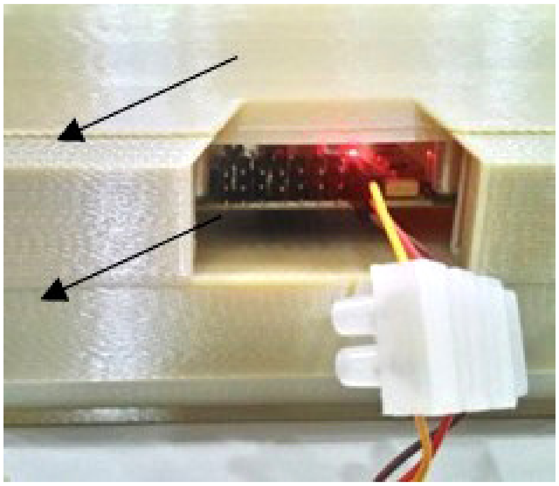

Figure 9 Weakened joints caused by thermal cooling

THERMAL ISSUES

The printer chamber had to be opened at different times in order to install the hardware, which could have caused cooling of the structure as it printed. To prevent cooling, the door was only open for less than five minutes at a time.

The second and third pauses were the most complicated, and if the door was kept open for too long, the drone would contract as it cooled, resulting in the drone and external support structure separating from the build tray. This could have caused misalignment upon resuming printing, ruining the entire print job.

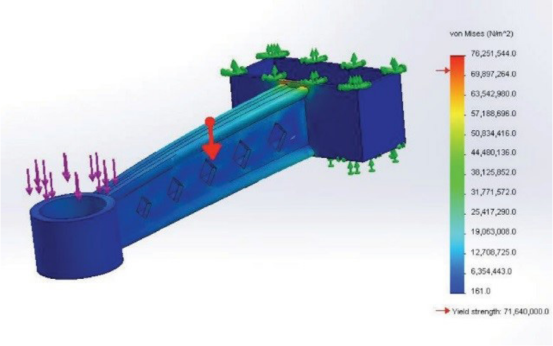

Figure 10 The static loading simulation showed a failure of the part at an equivalent of 20 kg.

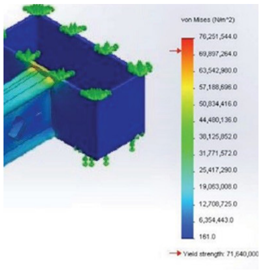

Figure 11 Close up showing the stress concentration (Von Mises plot).

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Figure 12 Real life test showed a part failure at 17 kg loading. The location of the stress concentration was the same as in simulation.

Figure 9 shows the effects of opening the door for prolonged periods of time. A visible layer shows where the preceding structure has shrunk during cooling. This is not an aesthetic defect; it is mechanically weakened at these layers.

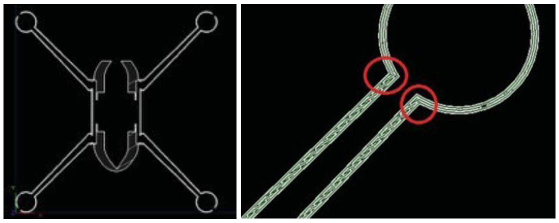

Figure 13 Weak points due to toolpath design

CONCLUSIONS

The drone printing was a success, the drone flew well and performed as predicted.

The final dry weight of the structure (plus motors) was 1050 grams. With the addition of the battery, the total weight was 1501 grams. This is very heavy for a 400-mm class quadcopter, which affects the maneuverability in the vertical direction. Ideally, the structure should be reduced by around 250 grams.

The angle limiter worked, and the drone remained stable during flight, proving that the accelerometers and gyroscopes were working correctly.

The main improvements would be enhancing the accessibility during the print process for hardware installation and we hope to add altitude hold and position hold for flight to any future iterations.

This would require heat testing the Naze 32 board full version, which contains barometer and magnetometers. The barometer and magnetometer should be able to resist print temperature for approximately four hours. Alternatively, the structure could be redesigned in order to reduce the time that the hardware is inside the printer.

Figure 14 The finished drone, painted and ready to fly.

APPENDIX

ULTEM 9085 RESIN DRONE STRENGTH

The entire drone featured wall thicknesses of 2 mm, which according to FEM analysis, enabled each arm to withstand a loading equal to 20 kg per arm.

Real life load testing showed this value was closer to 17 kg per arm, before the part failed. As a distributed load, this means that the drone can carry 68 kg supported from the arms. Note: This is not to be confused with the drone's aerodynamic lifting capacity (which is closer to 250 grams of extra payload).

Although the arms are capable of holding 68 kg collectively, there was some weakening at the motor housings. This was discovered after a plug became disconnected during the flight test. The drone fell from the sky from an altitude of around 20 meters resulting in cracks to two motor housings.

The locations of the cracks were at exactly the same position on each housing, implying that the cracks propagated in the same location due to the weld patterns.

Upon examination of the toolpath, the weakness was identified. In the future, this area should be reinforced with extra material or the toolpath should be modified to create a continuous path.

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