ARL-TR-9606 ● OCT 2022

DEVCOM
ARMY RESEARCH
LABORATORY

Design and Analysis of a Small Unmanned Aerial System (UAS) Power Distribution System

by Darren R Webb

Approved for public release: distribution unlimited.

NOTICES

Disclaimers

ARL-TR-9606 ● OCT 2022

Design and Analysis of a Small Unmanned Aerial System (UAS) Power Distribution System

Darren R Webb
DEVCOM Army Research Laboratory

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* October 2022	**2. REPORT TYPE** Technical Report	**3. DATES COVERED (From - To)** January 9, 2021–December 9, 2022

4. TITLE AND SUBTITLE Design and Analysis of a Small Unmanned Aerial System (UAS) Power Distribution System	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Darren R Webb	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) DEVCOM Army Research Laboratory ATTN: FCDD-RLW-TD Aberdeen Proving Ground, MD 21005	**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-TR-9606
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

All electrically powered autonomous vehicles possess a system that distributes power to all the vital components of the vehicle. The US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL) uses group 1 unmanned aerial systems (UASs) (weighing 20 lb) as the vehicle platform in several projects. These UASs are very fast and agile quadrotors, which typically have four rotors and light payloads, and can very quickly accelerate and effortlessly reach speeds over 100 kph, which require them to draw upward of 400 A at 30 VDC in bursts. As such, the motor/propeller combination requires large amounts of power relative to the size of the UAS. Up until this point, ARL UASs have been using commercial off-the-shelf power distribution boards (PDBs) to meet the power demands. A custom PDB would satisfy the DOD’s desire to source more UAS components domestically as it would be US designed and made, which is unique for this type of UAS component. This report considers the design of a custom PDB to include shape, size, components, cost, voltage regulators, peripherals, and so on. This report can be used as a starting point for engineers who are working on semiautonomous and fully autonomous vehicle projects.

15. SUBJECT TERMS

Energy Sciences; Mechanical Sciences; Photonics, Electronics, and Quantum Sciences; unmanned aerial system; UAS; power distribution board; PDB; group 1 UAS; autonomous vehicle; printed circuit board; PCB design

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Darren R Webb
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	UU	35	**19b. TELEPHONE NUMBER (Include area code)** (410) 278-6219

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

1. Introduction

All electrically powered autonomous vehicles possess a system that distributes power to all the vital components of the vehicle. At the US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL), several projects are using unmanned aerial systems (UASs) as a vehicle platform. Some UAS being used are classified as group 1, meaning they weigh under 20 lb. The group 1 UASs that ARL conducts research with are very fast and agile quadrotors. Such quadrotors typically have four rotors and light payloads and can very quickly accelerate and effortlessly reach speeds over 100 kph. To do this, these quadrotors can draw upward of 400 A at 30 VDC in bursts. To meet those requirements, the motor/propeller combination requires large amounts of power relative to the size of the UAS.

Up until this point, ARL's UASs have been using commercial off-the-shelf power distribution boards (PDBs) to meet the power distribution demands. A custom PDB would satisfy the DOD's desire to source more UAS components domestically, as it would be US designed and made, which is unique for this type of UAS component.

This report considers all aspects of design of a PDB to include shape, size, components, cost, voltage regulators, peripherals, and so on. This report explores these issues in the context of a custom-designed PDB needed for a specific ARL project, but can be used as a starting point for ARL engineers who are working on semiautonomous and fully autonomous vehicle projects.

2. Requirements

For the custom PDB to succeed, the board needs to perform just as well, if not better, than the current PDBs used on the UAS. The two PDBs this project currently uses are the following: Advanced Power Drives' (APD's) 500X (Fig. 1) and Matek Systems' FCHUB-12S PDB (Fig. 2).

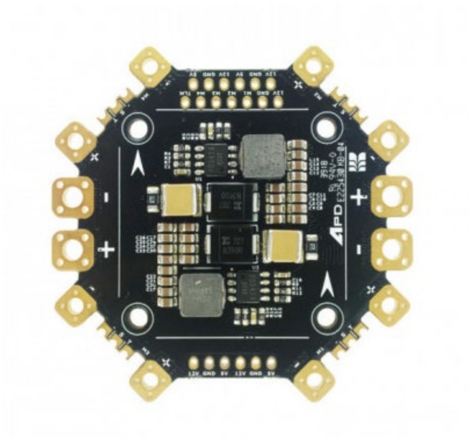

Fig. 1 Top view of APD's 500X PDB

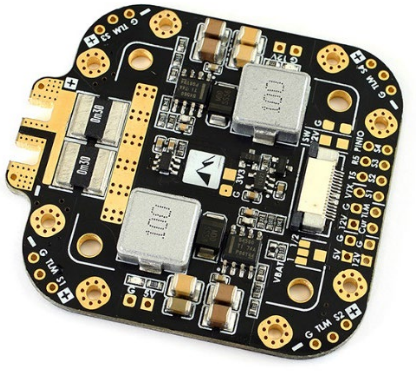

Fig. 2 Top view of Matek's FCHUB-12S PDB

The manufacturer-claimed specifications of the APD 500X are the following[1]:

- 4S–12S battery input
- 500-A continuous current
- 1000-A burst current

The manufacturer-claimed specifications of the Matek FCHUB-12S are the following[2]:

- 3S–12S battery input
- 280-A continuous current
- 440-A burst current

Both designs use the standard M3 × 0.5 mm with 30.5- × 30.5-mm mounting holes, and they both have the ability to provide ESC telemetry, battery voltage readings, current readings, and 5-V and 12-V outputs.

To be a suitable replacement for either of these PDBs, the custom PDB must be able to do the following:

- Accept up to 6S batteries.
- Handle continuous current draw of over 500 A.
- Handle burst current draws over 1000 A.
- Provide ESC telemetry.
- Provide voltage and current readings from the PDB.

3. Design and Theory

The program used to design and create the custom PDB is a free PCB/schematic application called KiCad. The main competitors to KiCad are Eagle and Altium. The reasons for using KiCad over the other two applications was because KiCad is compatible with the Windows, OSX, and Linux operating systems. Thus, projects can easily be transferred between workstations with little difficulty. The other reason is because KiCad is supported by popular electronics vendors, such as Digi-Key and Mouser, which offer free KiCad models for components that one might plan to use in a design.

To meet our requirements, the PDB needs to contain specific components exclusive to the custom PDB. At its core, a PDB is just a board with large copper traces with exposed pads to provide a positive and negative connection to the power source. The other supporting components that are required for our build are the following:

- Shunt resistors (to create a voltage drop)
- Current sensors (to measure battery voltage and current draw)
- Various capacitors and resistors (to complete the recommended circuits on the board)

Before creating a custom board, one must first create the schematic. The schematic for the first prototype, broken into four main components, is shown in Fig. 3.

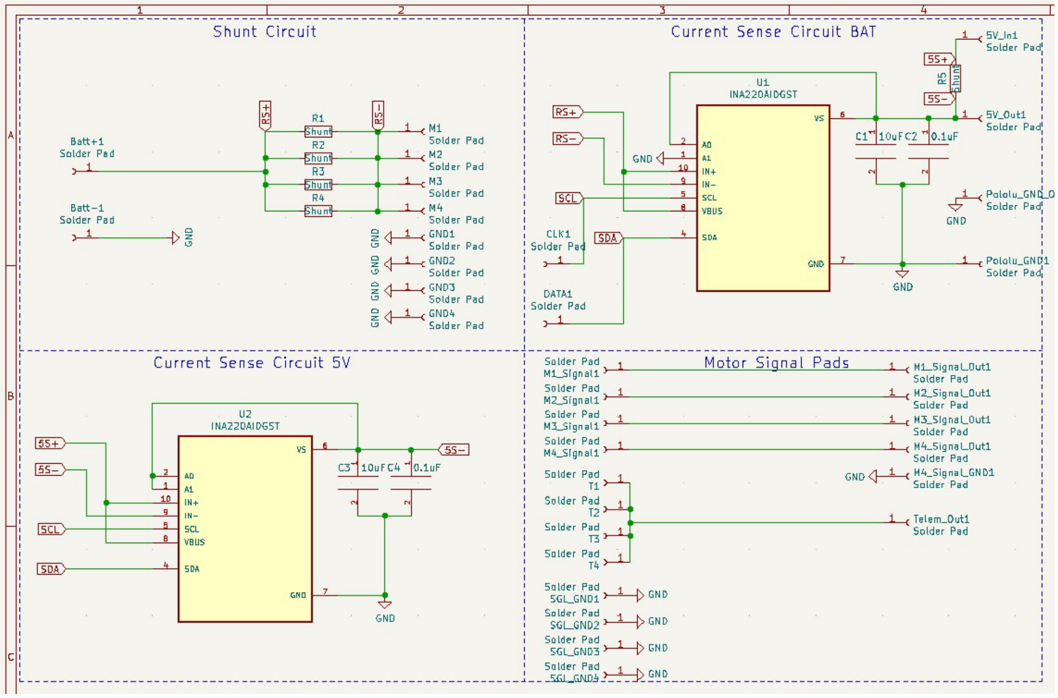

Fig. 3 **A detailed schematic of the circuits that will exist on the custom PDB**

A closer look at the shunt circuit (Fig. 4) shows the two main solder pads (on the left) that the positive and negative leads of the battery connector will solder to. It also shows four shunt resistors in parallel that will eventually distribute the positive battery voltage to four motor outputs (the ESCs connect here), and each motor output has a ground.

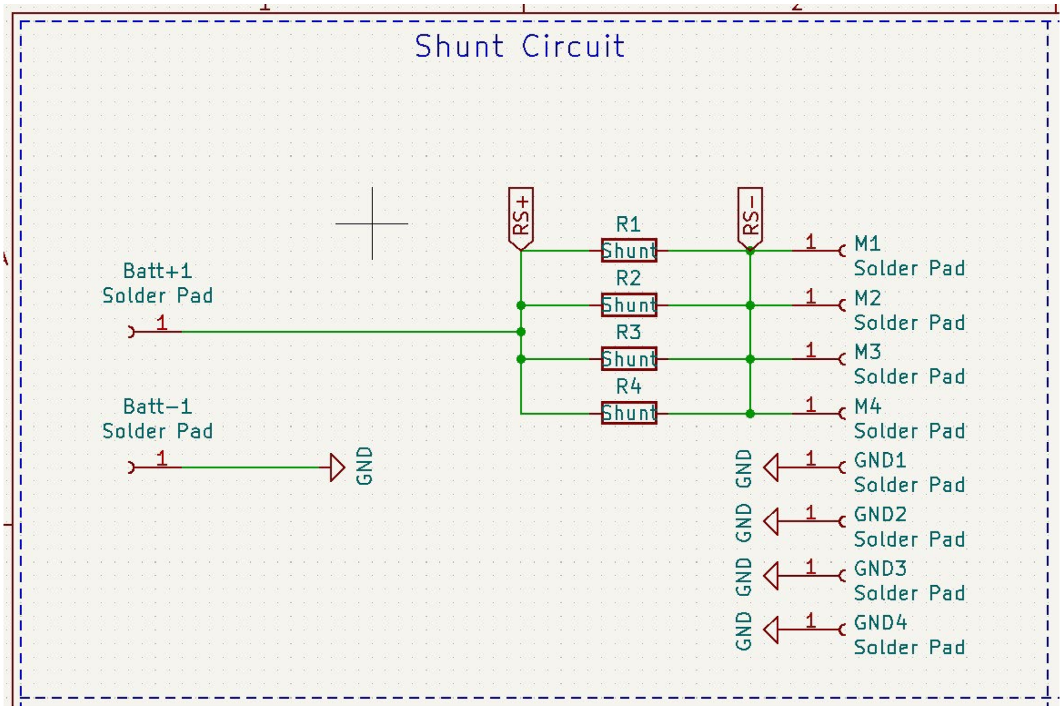

Fig. 4 **A detailed view of the shunt circuit on the custom PDB**

The purpose of the four shunt resistors in parallel is to provide a small voltage drop across them that can be measured and associated with a current that the flight computer can see and relay back to the operator. The voltage drops (RS+ and RS-) are measured in the current sensing circuit (Current Sense Circuit BAT section of the schematic), as shown in Fig. 5.

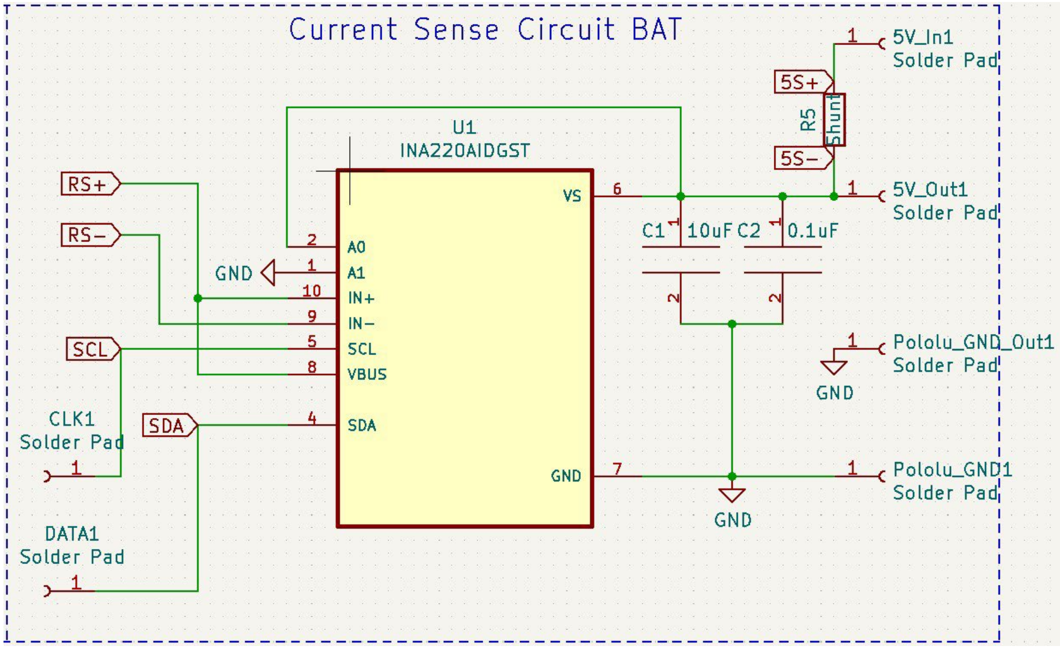

Fig. 5 A detailed view of the current sensing circuit on the custom PDB

To calculate the resistance needed that the shunt requires, four questions must be answered:

- What current sensing chip is being used?
- How much current is the system expected to draw at most?
- What voltage will the system operate at?
- How much power do the resistors need to dissipate?

To answer the first question, the current sensor typically used on an ARL UAS is an INA220. This is because the onboard flight computer (a ModalAI VOXL Flight Deck) normally uses a proprietary power module to power the computer and flight controller (Fig. 6). This power module also provides current sensing capabilities using the INA231 chip. This chip uses the i2c communication protocol to provide the flight controller with battery voltage readings and current readings. The reason for selecting the INA220 over the INA231 is because the INA220 is a surface mount chip with pins to solder to as opposed to the INA231 ball grid array. Assembling PCBs with ball grid array chips is extremely difficult to do without expensive manufacturing equipment. The INA220 offers very similar performance characteristics as the INA231 and uses the same i2c address. This essentially makes the custom PDB "plug-and-play" with the current flight computer.

Fig. 6 ModalAI's power module for most ARL UAS applications

To answer the second question, we expected to draw at least 500 A, since that is what the APD 500X can handle continuously.

As for the operating voltage, we use 6S batteries on the UASs, so the input voltage will not exceed 25.2 V.

Finally, for the expected power dissipation, we simply use Ohm's law for power:

$$P = I * V \tag{1}$$

We know the expected current is (500 A) and, based on the INA220 datasheet,[3] the measurable voltage drop range is in the tens of millivolts. For reference, we use 40 mV. Thus, per Eq. 1, we get 20 W.

Unfortunately, 20-W shunt resistors do not exist and, if they did, would be too large for the 30.5- × 30.5-mm platform. The easiest solution to this issue is to use shunt resistors in parallel. From here, it was a guess-and-check selection until a suitable group of resistors could be determined. The best solution found was a 9-W, 200-µΩ shunt resistor sold by Digi-Key. Placing four of these resistors in parallel fulfils the requirements for current sensing.

Now solving for I,

$$P = I^2 * R, \tag{2}$$

which gives us 848 A.

The calculations for the shunt resistors are promising and show that there will be no limitation from the shunts on the custom PDB. Note that the UAS is unable to pull currents beyond 848 A at the time of documentation.

The third section of the schematic covers the 5-V current sense circuit (Fig. 7).

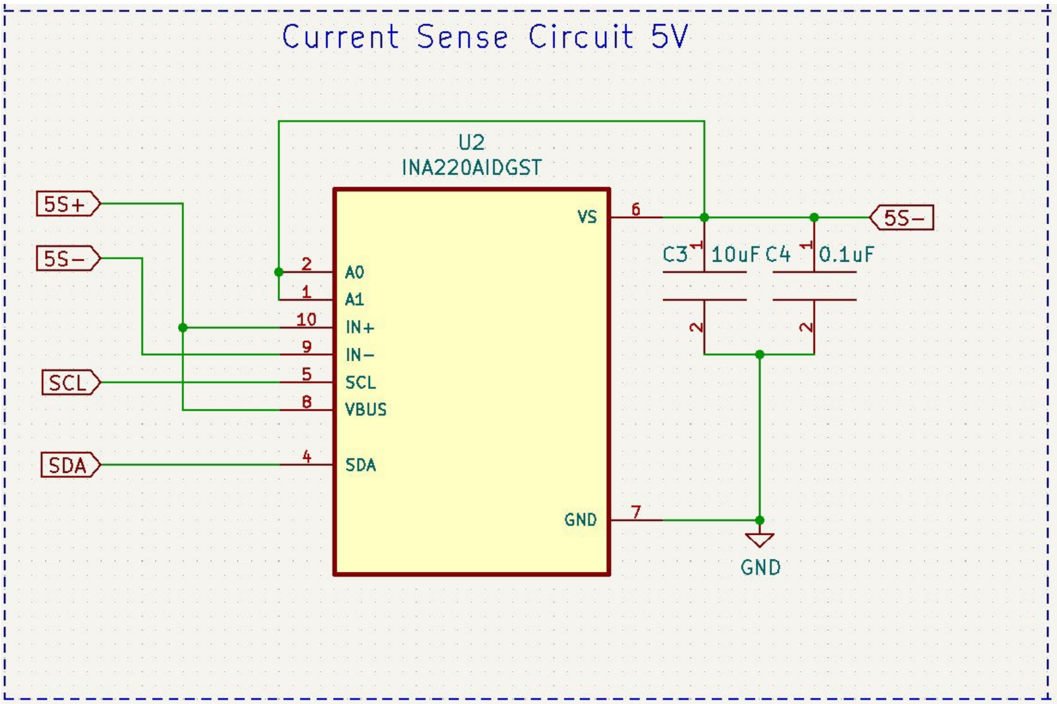

Fig. 7 A detailed view of the 5-V current sensing circuit on the custom PDB

The purpose of this circuit is to measure the current draw from the 5-V regulator on the UAS. This circuit is a passthrough circuit and the regulator does not live on the PDB. The same concept as described earlier is applied to calculate the shunt needed to handle 5 V at 9 A. The shunt being used is a 5-mΩ, 0.25-W resistor. Note the i2c address on this INA220 was changed so as not to interfere with the other INA220 on the same i2c data and clock lines.

The last section of the schematic illustrates the motor, signal, and telemetry solder pads on the custom PDB (Fig. 8).

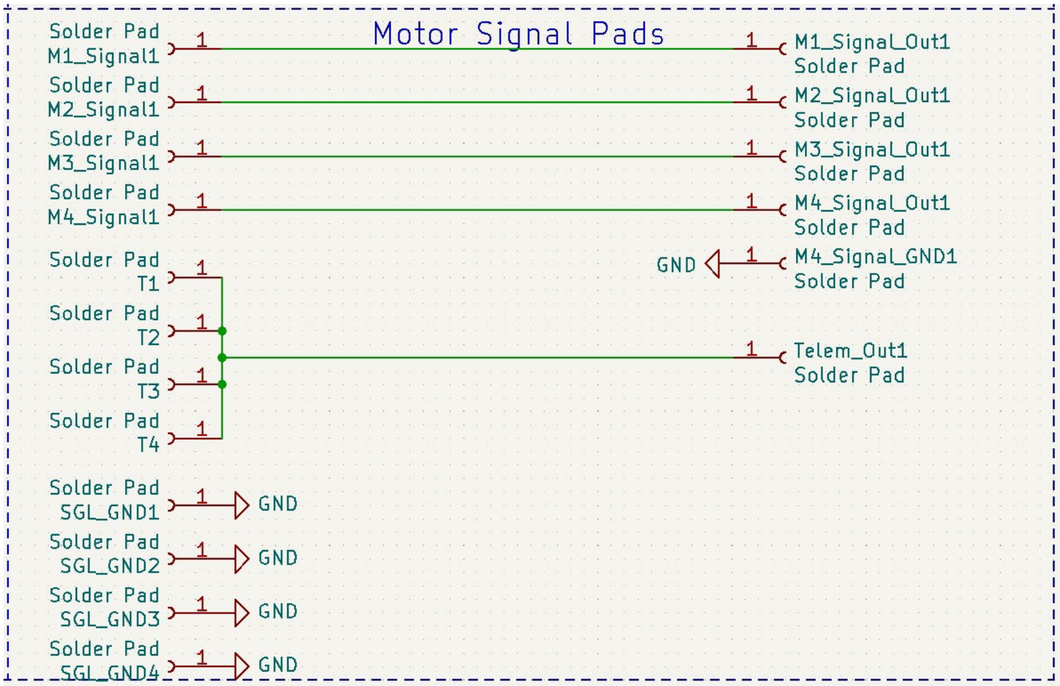

Fig. 8 A detailed view of the solder pad connections on the custom PDB

With the schematic design in place, the custom PDB can now take shape. Based on how APD and Matek design their PDBs, we decided to follow their design specifications as closely as possible. To start, the custom PDB contains eight layers of copper; APD and Matek use eight and six layers, respectively. Second, the finished weight of the copper must be no more than 6 oz. This is because APD and Matek both use of total of 4 oz of copper. Last, the PDB footprint should not be significantly smaller or larger than the APD or Matek's designs. The resulting 3-D design ended up with the same footprint as the Matek PDB: 8 mm thick Figures 9–11 show the final 3-D custom PDB created.

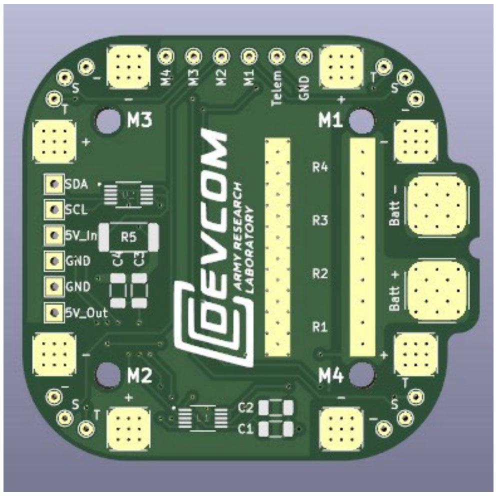

Fig. 9 Top view of the final 3-D model of the custom PDB

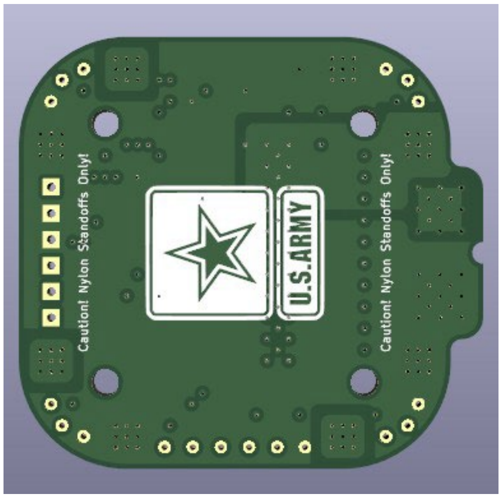

Fig. 10 Bottom view of the final 3-D model of the custom PDB

Designing 8-layer boards can be difficult and can easily turn into a mess of trace copper pours. To avoid this, one should follow this series of rules when routing traces and pouring copper for a custom PDB:

- Follow best "gridding" practices for all small electrical traces:
    - "Gridding" is a strategy used commonly by PCB design engineers where all traces that need to run horizontally (left to right) are routed on odd layers (1,3,5…, etc.) and all traces that need to run vertically (top to bottom) are routed on even layers (2,4,6…, etc.) or vice versa.
- Route all small electrical traces on layers 1 and 2.
- Run all positive battery copper pours on layers 1–4.
- Run all ground battery copper pours on layers 5–8.

While these rules cannot always be followed perfectly, they offer a good baseline to follow, and when exceptions need to be made, the process does not require a major redesign. All the eight layers can be seen in Figs. 11 and 12.

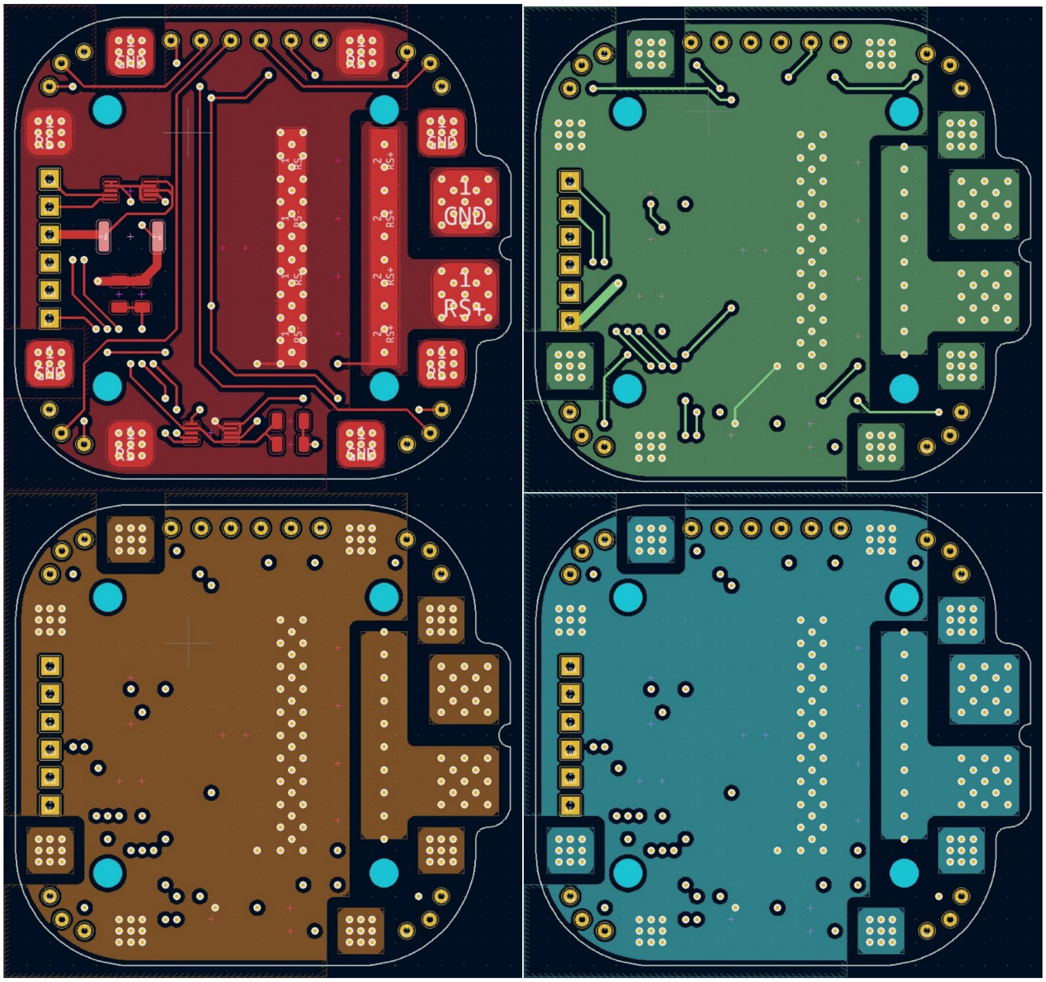

Fig. 11 Layers 1, 2, 3, and 4 (red, green, brown, and blue, respectively) of PDB. Notice all small electronic traces were routed on layers 1 and 2.

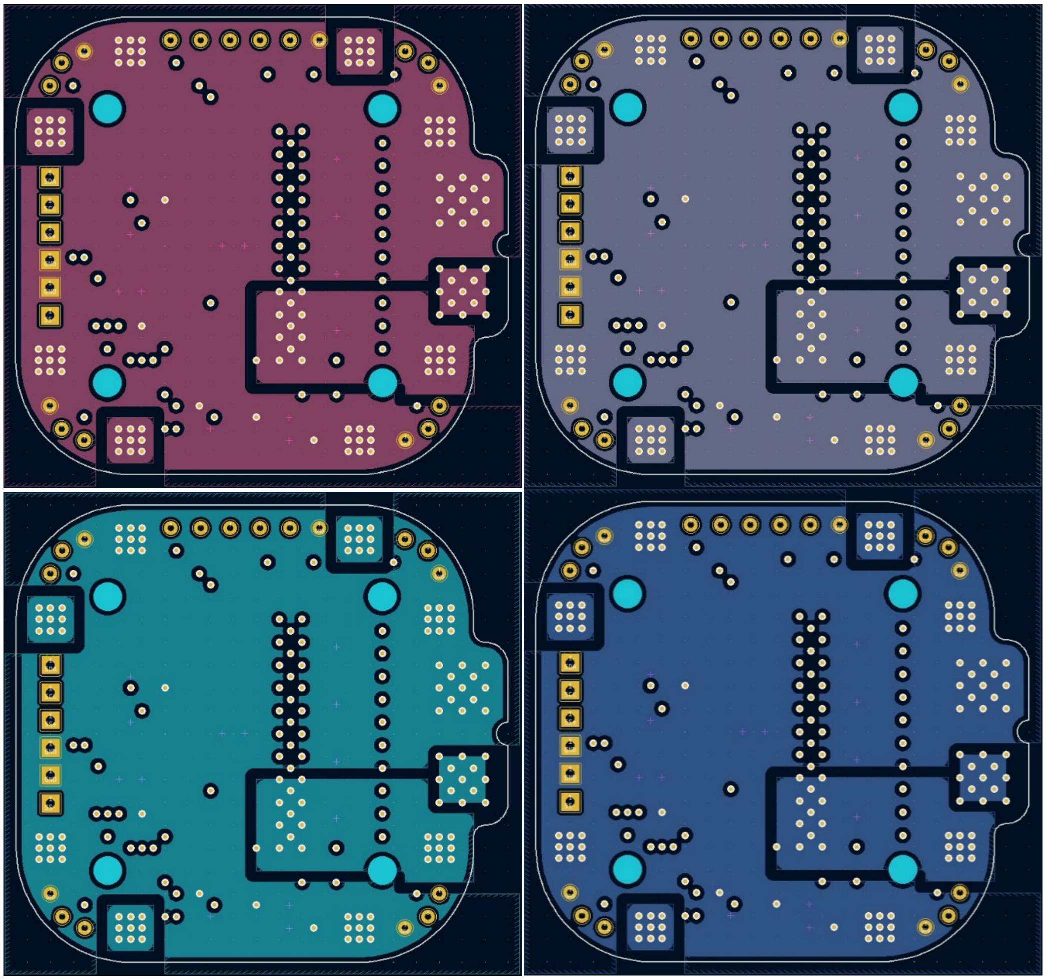

Fig. 12 Layers 5, 6, 7, and 8 (magenta, purple, blue, and royal blue, respectively) of PDB. These four layers are the ground plane.

As shown, most of the rules were followed when designing our custom PDB and its eight layers. Layers 1 and 2 differ the most from the rules, since they have all the traces for the smaller circuits onboard, like the current sensing circuits. As for the copper pours, layers 1 and 2 differ slightly from each other and layers 3 and 4, but still deliver power to all four motor pads. Layers 5–8 are identical, since there are no small circuit traces present. All copper pours were connected by multiple vias scattered around the board in various locations to make sure there were no isolated copper islands and to distribute the current load evenly between pours.

4. Costs

The first prototype of the board was ordered through Screaming Circuits. They offer custom PCB services and are one of the only companies that will do custom copper density, multiple layers, and custom shapes, all things this custom PDB required. To manufacture 10 boards, the cost was $145.68 per board with an additional tooling fee of $430.00, which means each unassembled board costs $188.68. With electrical components being in short supply, the vendors and prices for the other components to complete the board can vary. Roughly, it costs about $50.00 in parts per board. This brings the final total to $238.68 per board. For reference, the APD 500X costs $80.00 per board and the Matek FCHUB-12S costs $26.00 per board. Although our custom board is more expensive, it is made in the United States and meets the specific needs of our UAS.

5. Test Setup and Results

To validate that the first prototype was a success, a series of tests was performed on each of the PDBs. The test plan is as follows:

- 80-A current draw
    - 10 s – record temperatures.
    - 30 s – record temperatures.
    - 60 s – record temperatures.
- 180-A current draw
    - 10 s – record temperatures.
    - 30 s – record temperatures.
    - 60 s – record temperatures.
- 200-A current draw
    - 10 s – record temperatures.
    - 30 s – record temperatures.

Although we wanted to test at higher currents and until eventual failure, we were limited by the size of the power supply on hand and popping a 220-V breaker. The power supply used was a Xantrex XDC 30-200 (Fig. 13). The power supply must be run from 220 VAC and can provide voltages up to 30 and 200 A max. To validate if the custom PDB operated as desired, temperatures were recorded to ensure that the PDB was not getting hotter (or too much hotter) than the Matek and APD boards.

Fig. 13 Power supply used for testing

The test stand used was a mobile cart on which we mounted all of the hardware (Fig. 14). To pull that amount of current through each motor pad, we used Ohm's law for voltage to figure out what size resistors were needed (except for 200 A, since the power supply is current limited). To start, for 80 A (26 V at 20 A each motor),

$$V = I * R, \tag{3}$$

which results in $R = 1.3\ \Omega$,. For 26 V at 180 A, this results in R = 666 mΩ. For 26 V at 200 A (limited), this results in R = 300 mΩ,

To test at these currents and resistances would require power resistors that do not currently exist on the market. To compensate for this, nichrome was used to create custom homemade resistors. Nichrome is often used in appliances such as electric stoves, toasters, and space heaters. The nichrome we had on hand measured 100 mΩ per foot and could easily be cut and bent into coils. So we made four 1.3-Ω coils, four 600-mΩ coils, and four 300-mΩ coils.

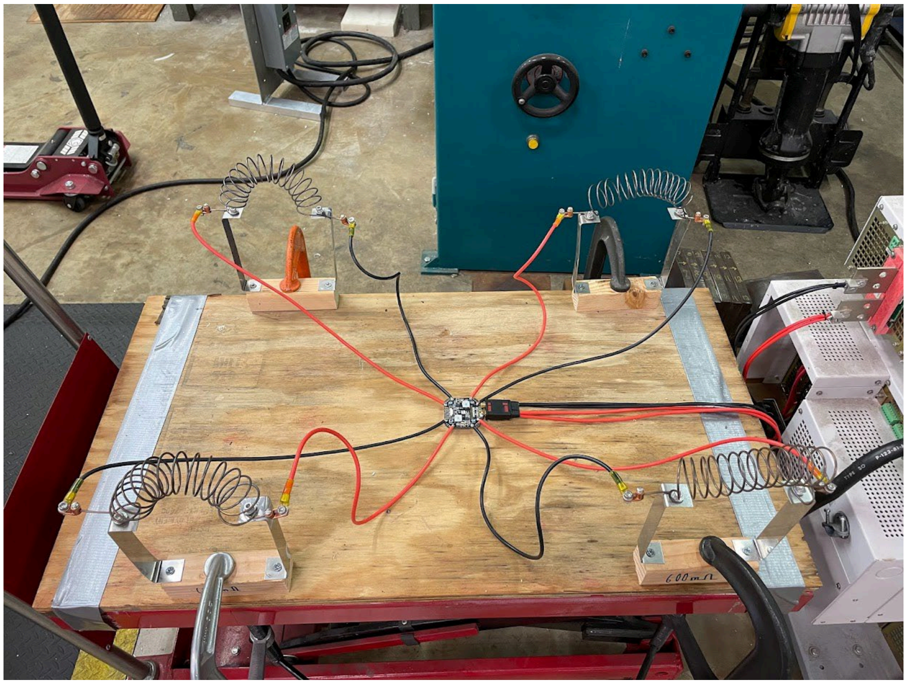

Fig. 14 PDB and coils secured to the mobile test bench. Each test repeated looked similar to this with the coils and PDBs changing.

The ambient conditions for all tests conducted were the following:

- 95 °F
- 65% humidity
- 29.98-inHg barometric pressure

Figure 15 shows the test for 80 A at 10 s.

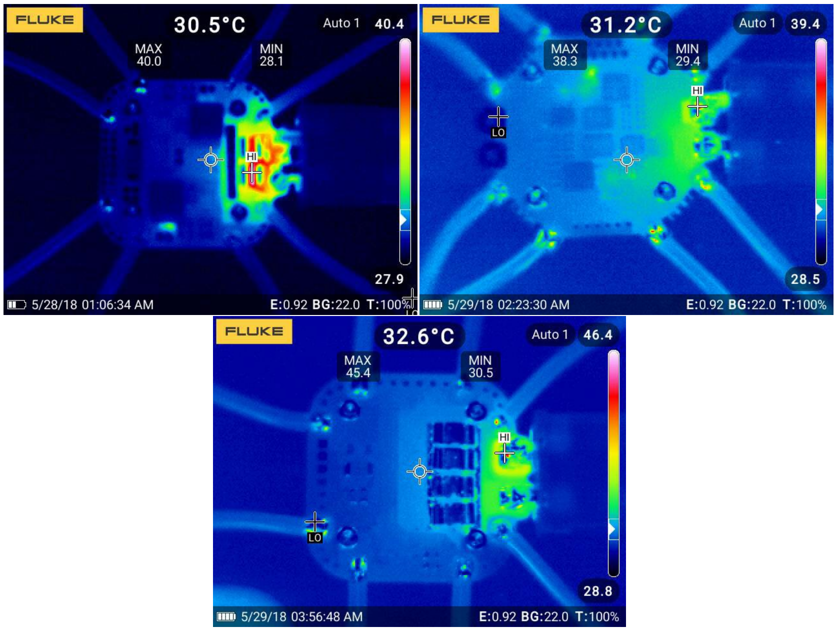

Fig. 15 **(Left to right) Matek, APD, and custom. The custom reported the highest temperature reading at 45.5 °C at the solder joint, while the APD reported the lowest max 38.3 °C at the solder joint.**

Figure 16 shows the test results for 80 A at 30 s.

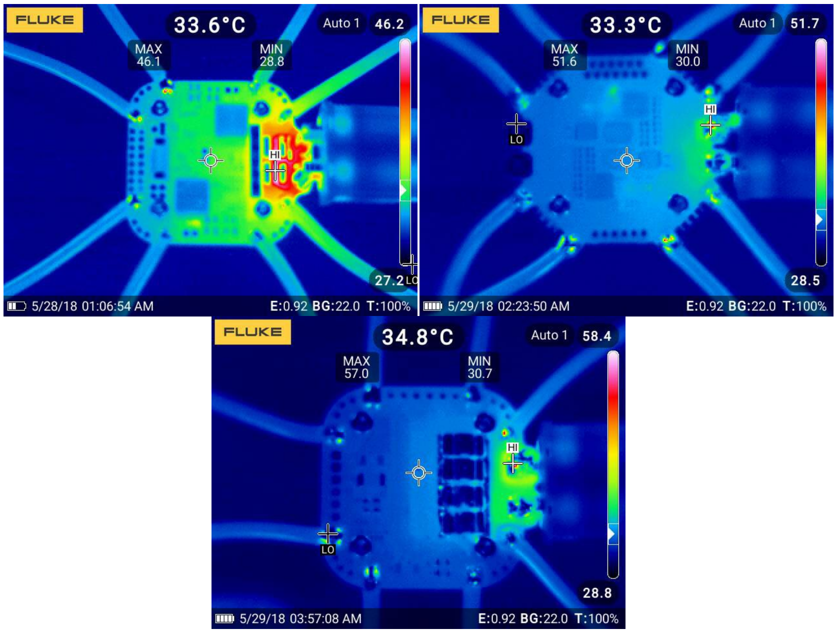

Fig. 16 **(Left to right) Matek, APD, and custom. The custom reported the highest temperature reading at 57.0 °C at the solder joint, while the Matek reported the lowest max 46.1 °C at the shunt resistor. However, the Matek board is saturating with heat more quickly than the other two boards.**

Figure 17 shows the test results for 80 A at 60 s.

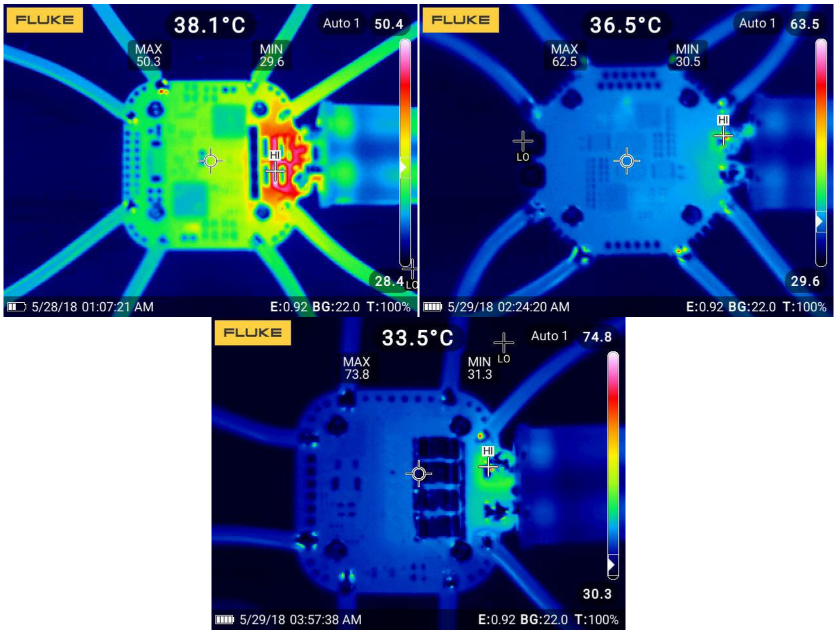

Fig. 17 (Left to right) Matek, APD, and custom. The custom reported the highest temperature reading at 73.8 °C at the solder joint, while the Matek reported the lowest max 50.3 °C at the shunt resistor. However, the Matek board completely saturating with heat at 38.1 °C and the APD is at 36.5 °C while the custom is at 33.5 °C .

Figure 18 shows the test results for 180 A at 10 s.

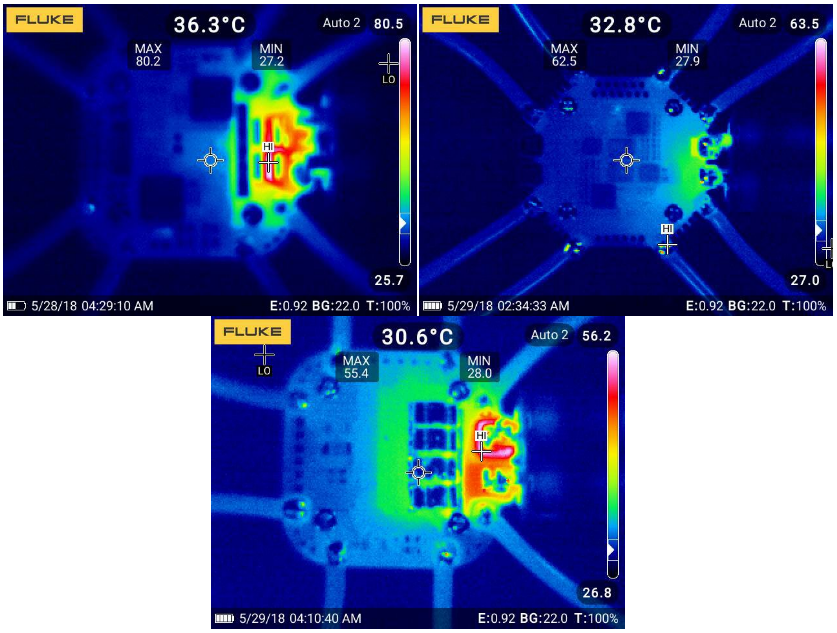

Fig. 18 (Left to right) Matek, APD, and custom. The Matek reported the highest temperature reading at 80.2 °C at the shunt while the custom reported the lowest max 55.4 °C at the solder joint. The Matek board was beginning to saturate at 36.3 °C, the APD was saturating at 32.8 °C, while the custom was not saturating at all yet at 30.6 °C.

Figure 19 shows the test results for 180 A at 30 s.

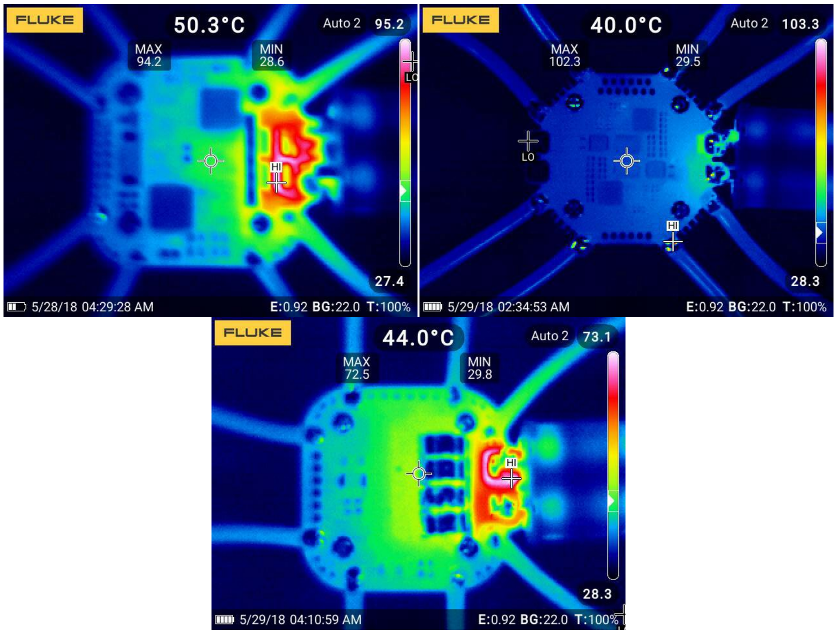

Fig. 19 (Left to right) Matek, APD, and custom. The APD reported the highest temperature reading at 102.3 °C at the solder joint while the custom reported the lowest max 72.5 °C at the solder joint. The Matek board was saturated at 50.3 °C, the APD was saturated at 40.0 °C, and the custom was saturated at 44.0 °C.

Figure 20 shows the test results for 180 A at 60 s.

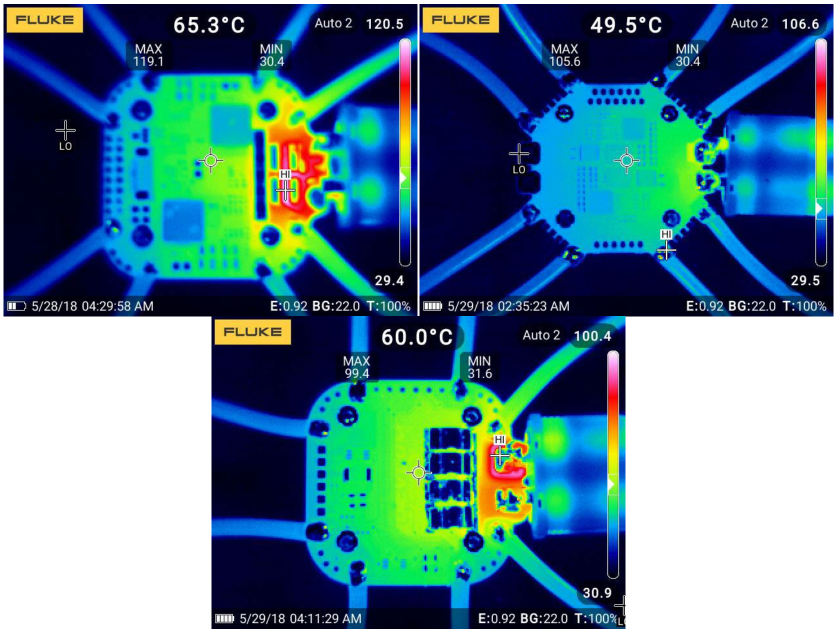

Fig. 20 (Left to right) Matek, APD, and custom. The Matek reported the highest temperature reading at 119.1 °C at the shunt while the custom reported the lowest max 99.4 °C at the solder joint. The Matek board was saturated at 65.3 °C, the APD was saturated at 49.5 °C, and the custom was saturated at 60.0 °C.

Figure 21 shows the test results for 200 A at 10 s.

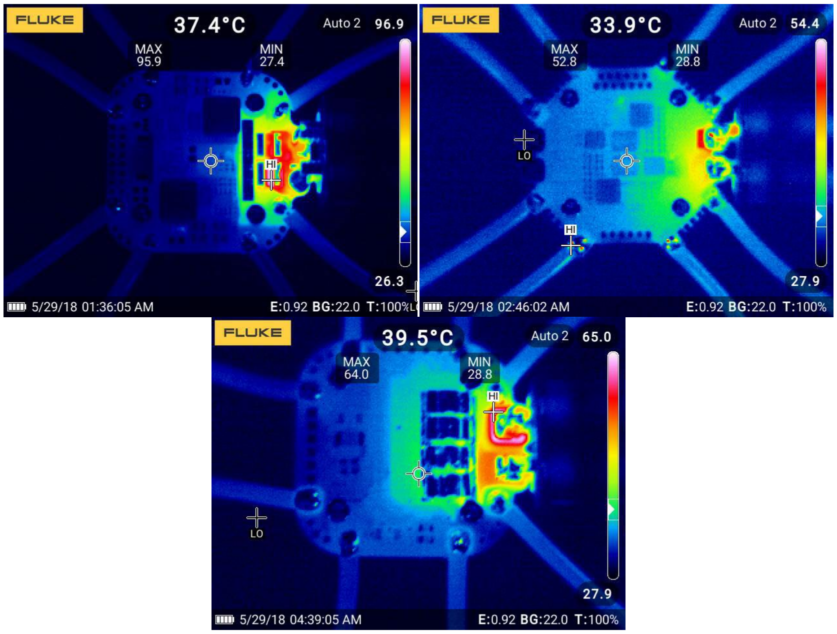

Fig. 21 (Left to right) Matek, APD, and custom. The Matek reported the highest temperature reading at 95.9 °C at the shunt while the APD reported the lowest max at 52.8 °C at the solder joint. The Matek board was saturated at 37.4 °C, the APD was saturated at 33.9 °C, and the Custom was saturated at 39.5 °C.

Figure 22 shows the test results for 200 A at 30 s.

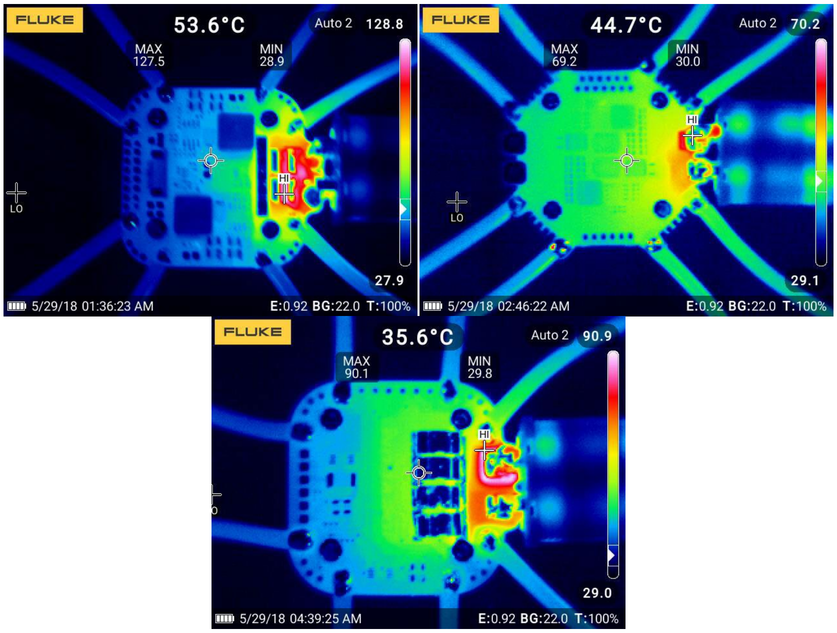

Fig. 22 (Left to right) Matek, APD, and custom. The Matek reported the highest temperature reading at 127.5 °C at the shunt while the APD reported the lowest max at 69.2 °C at the solder joint. The Matek board was saturated at 53.6 °C, the APD was saturated at 44.7 °C, and the Custom was saturated at 35.6 °C.

Practically, these preliminary results look very good for the custom PDB. Looking at the graphs for the 80-A test results (Fig. 23) provides the following takeaways:

- The custom PDB performed the worst out of the three PDBs but is still within acceptable limits for maximum temperatures.
- The custom PDB performed almost identically to the other two PDBs in the saturation temperature test:
    - The 60-s reading on the custom PDB may be anomalous since it is abnormally low.

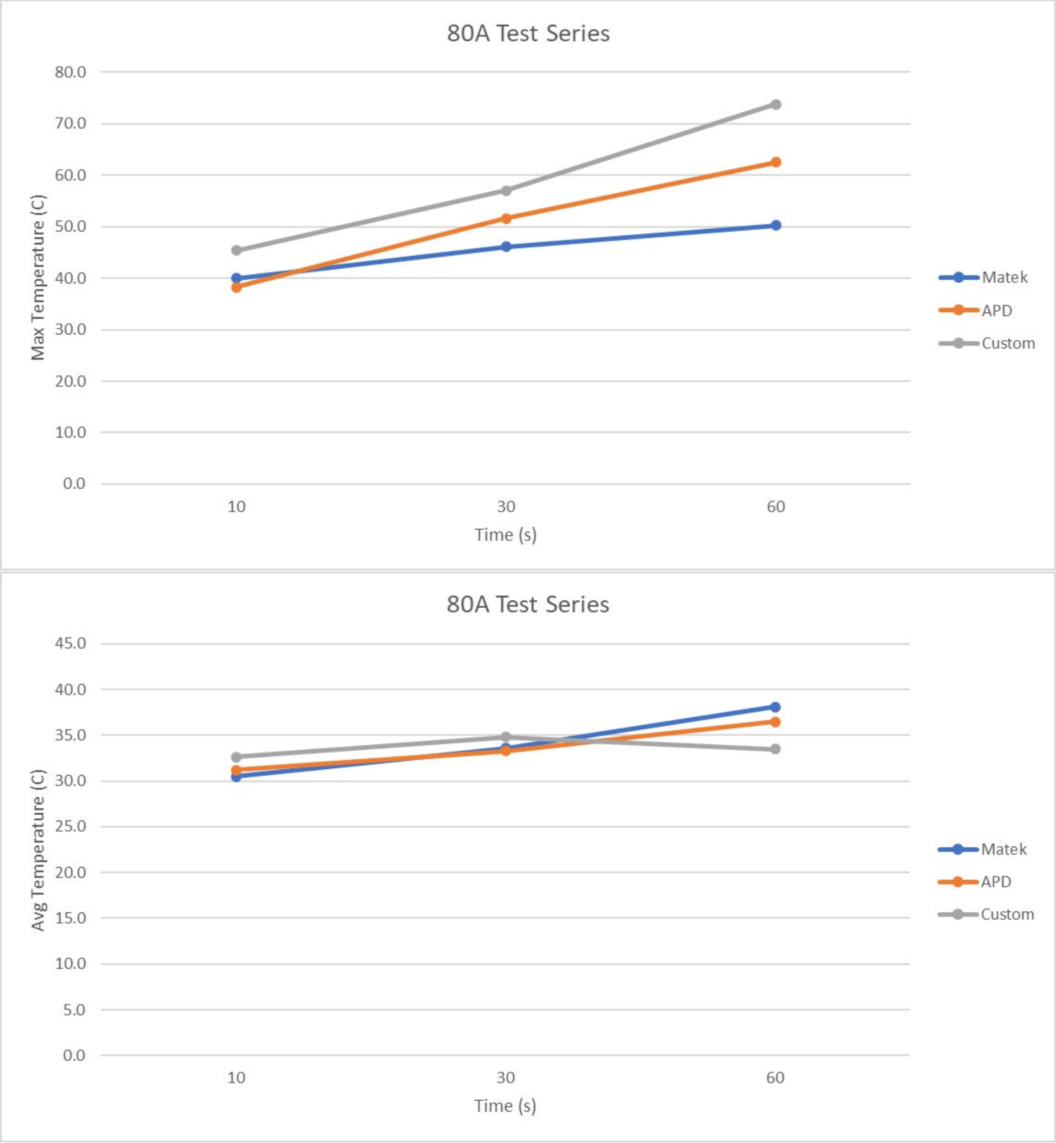

Fig. 23 Maximum (top) and average (bottom) temperature readings from the 80-A test series. The custom PDB performed well but not as well as Matek or APD.

For the 180-A test series (Fig. 24), the custom PDB starts to thrive amongst the boards. Looking at the graphs provides the following takeaways:

- The custom PDB could withstand the higher current better than the APD and Matek PDBs in the maximum temperature test.
- The custom PDB has a reasonable saturation temperature that is on par with the APD and Matek PDBs.

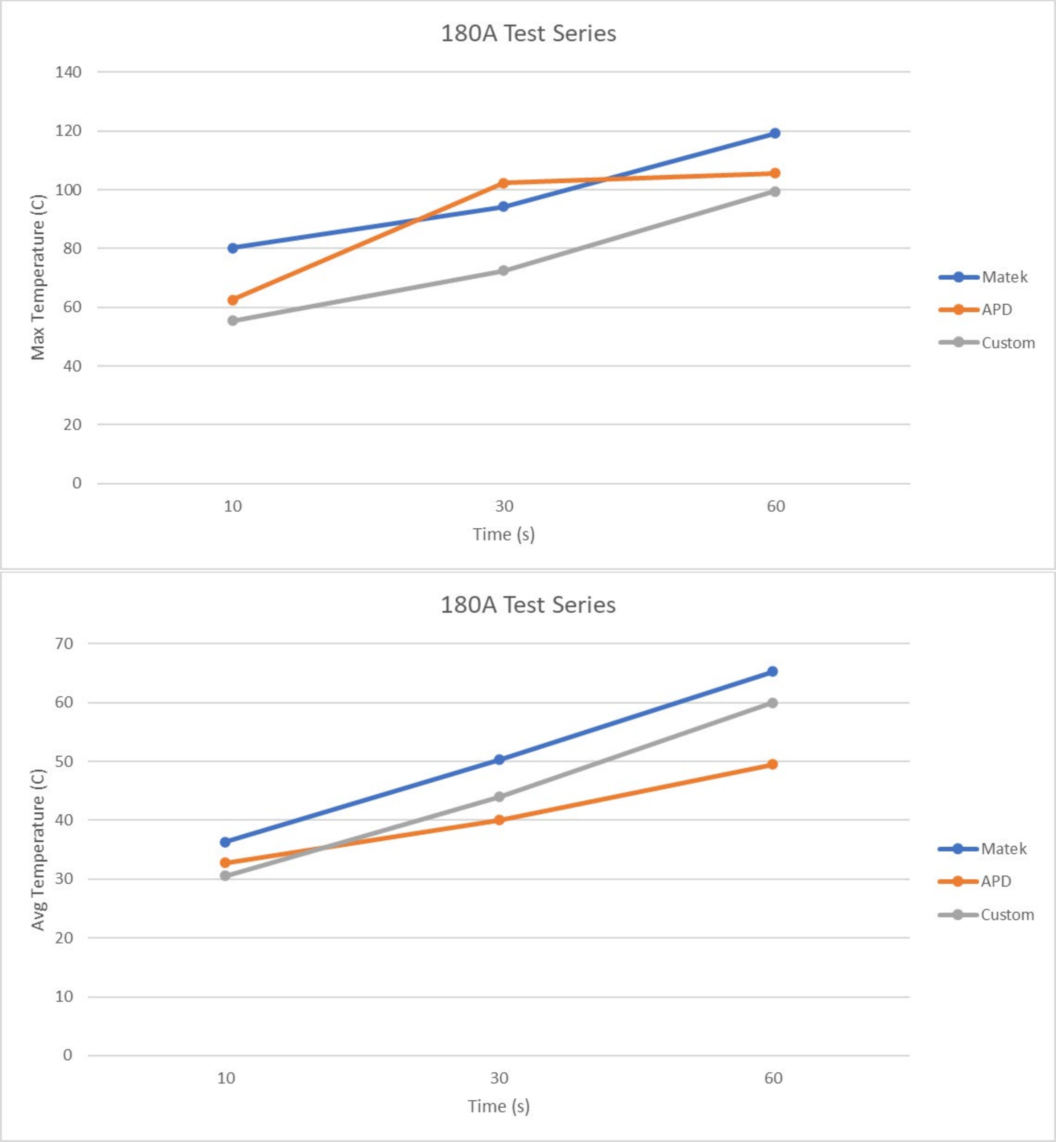

Fig. 24 Maximum (top) and average (bottom) temperature readings from the 180-A test series. The custom PDB performed better than the Matek and APD boards on the maximum temperature test and on par in the average temperature test.

For the 200-A test series (Fig. 25), the story is much the same as the 180-A test series. The custom PDB performs on par with the Matek and APD's offerings in the maximum and average temperature tests. Looking at the graphs provides the following takeaways:

- The custom PDB beats out the Matek PDB by a large margin in the maximum temperature test but was still edged out by the APD PDB.
- The custom PDB performed on par with the others during the average temperature tests:
    - The final reading of the custom PDB may be anomalous.

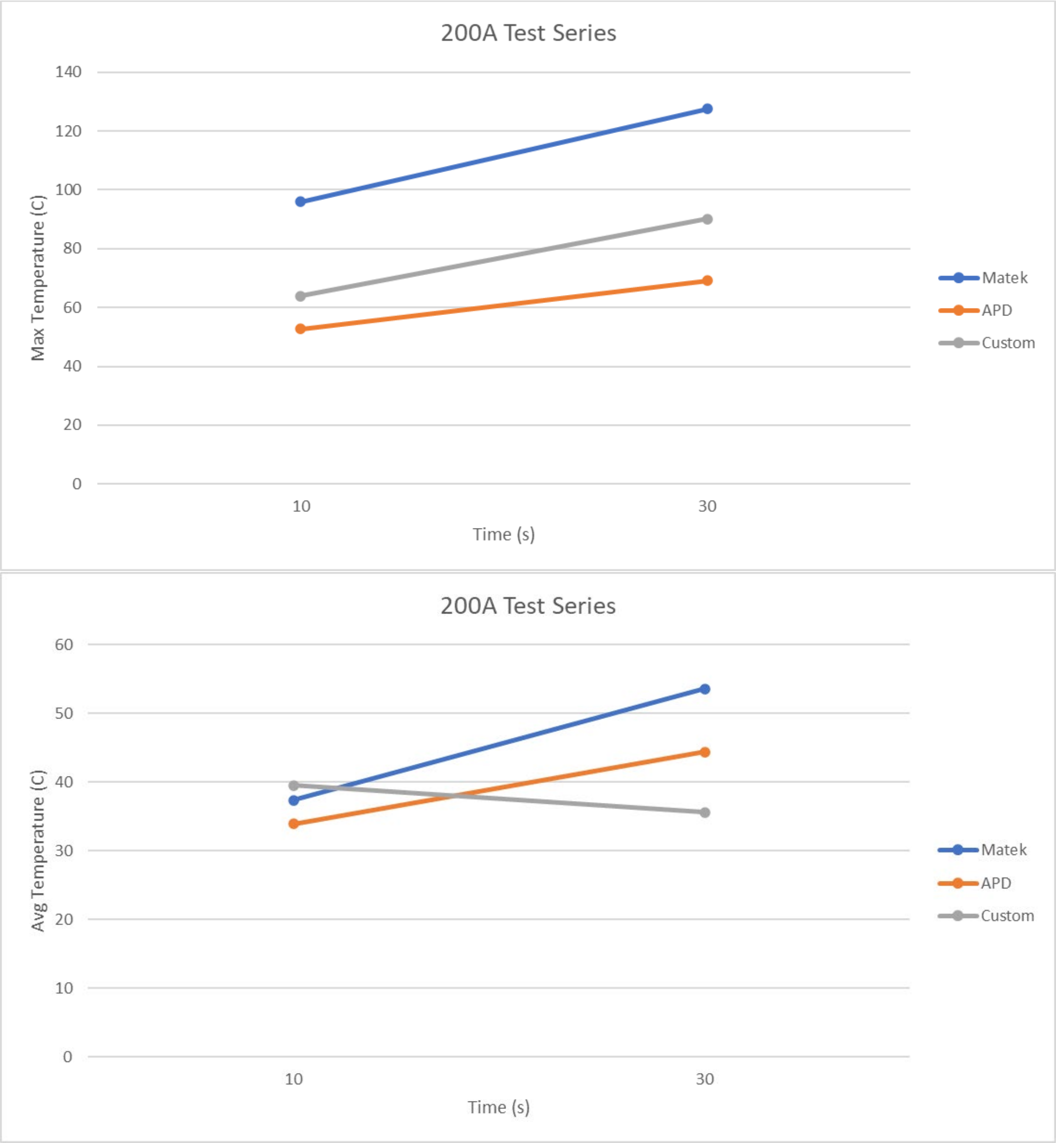

Fig. 25 Maximum (top) and average (bottom) temperature readings from the 200-A test series. The custom PDB performed right in the middle of the pack compared to the other PDBs on the maximum temperature test. On the average temperature test, the results followed what was expected based on the 80- and 180-A test series.

As a whole, the results seem to be very promising and reaffirm the expectations set before it. Aside from the two anomalous readings seen in Figs. 23 and 25, the results confirm what our calculations predicted. Ranking the PDBs, the APD PDB performed the best, the custom PDB finished second, while the Matek finished third. This is because the APD PDB outperformed the custom PDB in the 200-A test series but was on par during the 80- and 180-A test series. In addition to this, the APD PDB performed just slightly better than the other two in all the average temperature tests. This would place the custom PDB in second above the Matek

PDB, because it outperformed the Matek PDB in all tests while just barely trailing behind the APD.

Despite the differing results, all of the PDBs would more than adequately suit the needs of the ongoing research at ARL. To elaborate, under normal operating conditions a continuous current of 80 A is normal and describes the working state for 95% of the time. To draw 200 A is rare, and drawing 200 A for periods of time longer than 10 s is unheard of. That means that 95% of the time even the hottest areas of the boards will still be safe to the touch without burning one's hands. All of the components on the PDBs are rated to operate at temperatures of 100 °C (with exception of the shunts; they can run red hot). This series of tests also does not include any cooling provisions that could be put in place to help reduce the temperatures.

6. Future Work

Given the results, a number of improvements are planned for the next revision of the custom PDB. One of those improvements would be to reduce the number of copper layers from eight to six. This will bring the performance metrics down to Matek's level; however, it will reduce the size and weight of the product. Since the PDBs are all overbuilt for the task, it is not necessary to continue to use eight layers, as this adds nothing but additional size, cost, and complexity.

The second improvement needed would be to expand the PDB outward to accommodate all the hardware to which it distributes power. Doing this is for ease of assembly and maintenance, as being able to directly attach/bolt on hardware to an existing PCB will always be easier than soldering to solder joints/pads.

The final improvement to be made would be to move to a better Texas Instruments chip such as the INA237, rather than continuing to use the INA220. This is because the INA220 can only support voltages up to 26 V, whereas the INA237 can support voltage up to 85 V. In the future, the projects the custom PDB would integrate into may be operating at voltages above 50 V.

7. Conclusions

As the Army pioneers new technology for its existing UAS and new UAS to overcome the challenges of the battlefield, it is important to remember critical components like the PDB are being carefully scrutinized to ensure National Defense Authorization Act[4] compliance and make sure they work reliably in the vehicle into which they are installed. This report can be used as a starting point for ARL engineers who are working on semiautonomous and fully autonomous vehicle projects. For the UASs to which these PDBs will be mounted, this research will greatly improve the quality of development and testing, and represents a hurdle already conquered for future projects.

8. References

1. APD 500X datasheet. Advanced Power Drives; n.d. [accessed 2022 Sep]. https://1471056808-files.gitbook.io/~/files/v0/b/gitbook-x-prod.appspot.com/o/spaces%2F-LqA1iwil1ddpVBXp8FT%2Fuploads%2FE3TA8lMde47Br4vnNQXH%2FPDB500v1.2.pdf?alt=media&token=e488e50a-0978-4ea9-b398-bafa9dceaa97.

2. Matek’s product page with specifications for FCHUB-12S. Matek Systems; n.d. [accessed 2022 Sep]. http://www.mateksys.com/?portfolio=fchub-12s#tab-id-2.

3. INA220 datasheet. Texas Instruments; 2016 Jan [accessed 2022 Sep]. https://www.ti.com/lit/ds/symlink/ina220.pdf?ts=1658940892544&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FINA220.

4. National Defense Authorization Act Bill; 2021 Dec [accessed 2022 Sep] https://www.congress.gov/bill/117th-congress/senate-bill/1605/text.

List of Symbols, Abbreviations, and Acronyms

APD	Advanced Power Drives
ARL	Army Research Laboratory
DC	direct current
DEVCOM	US Army Combat Capabilities Development Command
DOD	Department of Defense
ESC	electronic speed controller
PDB	power distribution board
UAS	unmanned aerial system

1 DEFENSE TECHNICAL
(PDF) INFORMATION CTR
DTIC OCA

1 DEVCOM ARL
(PDF) FCDD RLD DCI
TECH LIB

1 DEVCOM ARL
(PDF) FCDD RLW TD
D WEBB