2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering
Education for 130 Years
Paper ID #39289

Design and Manufacturing Innovations in Modular Drone Design Enabled by Additive Manufacturing: Customizable Power Distribution Board

Dr. Firas Akasheh, Tuskegee University

Dr. Akasheh has been with the Mechanical Engineering Department at Tuskegee University since 2008. His primary interest is in the area of solid mechanics and manufacturing as well as the integration of best practices in engineering education.

Stephen Baker
Dr. Mandoye Ndoye, Tuskegee University

Mandoye Ndoye received the B.S.E.E. degree from the Rensselear Polytechnic Institute, Troy, NY, in 2002, the MS degree in Mathematics and the Ph.D. degree in electrical and computer engineering from Purdue University, West Lafayette, IN, in 2010. After co

Dr. David Shannon, Auburn University

Dr. Shannon has a Ph.D. in Educational Research and Evaluation Methodology and Statistics from the University of Virginia and is currently the Humana-Sherman-Germany Distinguished Professor at AU. He teachers courses in research methods and program evalua

josiah e blocus, Tuskegee University
Mr. Eugene Thompson

Design and Manufacturing Innovations in Modular Drone Design Enabled by Additive Manufacturing: Customizable Power Distribution Board

Additive manufacturing (AM) is a relatively recent development in manufacturing which represents a paradigm shift in the way parts are made. Creating parts layer by layer offers many benefits including the ability to create parts with high level of geometric complexity, while forgoing the need for molds and dies, vertical integration of design and manufacturing activities, and the facilitation of customization even at mass. In the area of product development those benefits make design iterations fast and inexpensive, which not only translate into shorter development cycle, but also empower engineers to innovate in way not possible before. In a preceding work, we showed how interdisciplinary team of students developing a modular quadcopter drone ideated, built, and tested several innovative concepts, all of which were enabled by AM. In this work, we extend the preliminary work on the development of a concept for a customizable 3D printed power distribution board to replace a typical commercially available PDB which will further support additional innovations in modularity and improved functionality. The students designed the board, built it using FDM 3D printing, and tested it under maximum load conditions to ensure its proper functioning without excessive heating. Preliminary testing showed that, within the normal operating time before battery recharging becomes necessary, the board's temperature increases by about 18 ^{o}F, which is acceptable. As a final step in the pursuit of this concept, the board was integrated into the drone body and a procedure for embedding the electric wiring was developed. This integration required several design modifications, which were implemented and prototyped. We believe that this modular drone development project design and mentorship guided by the principles of experiential learning and empowered by AM has increased the efficacy of students and helped them develop several skills that are valuable to the future engineering work force including team skills, leadership, time-management, life-long and interdisciplinary learning, and entrepreneurship mindset. Through a survey and focus group approach, the findings of an independent evaluator confirm those benefits to the students participating in the project.

1. Introduction

Additive manufacturing (AM), *aka* 3D printing, is a relatively new approach to manufacturing parts and prototypes which represents a paradigm shift and promises significant benefits in all sectors of industry. By gradually building the part layer by layer, AM reduces the complexity of 3D parts to that of 2D slices, hence can easily produce parts with extremely complex geometries. Additional, since AM does not require the use of molds and dies to produce a part, significant reduction in production cost and lead time can be achieved especially if prototypes or short production runs are needed. The implication of that for product development processes is significant. Besides shortening the product development cycle and lowering the cost, AM allows for vertical integration, bringing design and manufacturing closer to each other, while allowing for more innovative designs such as topology optimized lightweight parts, parts with improved heat management due to improved cooling channels, consolidated parts, and parts with embedded electronics and electric wiring. Additional benefits of AM include the flexibility of producing parts at remote location, on-demand production, distributed manufacturing, less material waste, and better management and resiliency of supply chains. For all the above advantages, AM continues to evolve and get adopted at accelerating rates by almost all industry sectors, with aerospace taking the lead in adoption for flight worthy parts. For such parts, the certification process is very challenging and lengthy given the novelty of AM and the inherent variability and uncertainty in the long-term performance of additively manufactured parts. Despite that, General Electric clearly demonstrated the potential of AM in the aerospace industry by developing and certifying the Leap engine fuel nozzle manufactured by AM [1]. Besides consolidating the 19-part old nozzle design into a one-part nozzle, AM made it possible for the nozzle to have more sophisticated fuel channels, leading to 25% fuel efficiency of the engine. A recent report by Grand View Research [2], indicates that the future market projections indicate that the total AM market will have a value of $62.79 billion in 2028, compared to $16.54 billion in 2021, at a growth rate of 21%.

In education and workforce training, AM is also playing a transformative role due to its unique benefits. Besides enabling the production of highly sophisticated instructive models and demonstrations, hence improving STEM education, AM is increasingly used as a vehicle to quickly, iteratively and feasibly allow students to build functional prototypes to test their conceived designs. AM can also help educate students about concurrent engineering, how the manufacturing plan for a part must be developed early on during the design process to make sure that design corrections and changes are not made late in product life cycle, where such changes become disruptive and costly. AM can also be instrumental in giving students hands-on experience with product development resulting in improved understanding and exposure to real-life product development practices. Furthermore, AM can unlock the creativity of students by enabling them to produce innovative parts with almost no restrictions on part geometrical complexity. Building on students' interest in drones, Tipker *et al.* [3] presented freshman engineering class basic drone electronics kit and asked them to design and build, using AM, suitable drone structure, assemble it, and fly it. In a senior capstone project, Hur *et al.* [4] demonstrated how students used AM to manufacture metal and plastic propellers for small-scale thrusters for underwater robots. Rios [5], 3D-printed and compared them to their CAD models to illustrate several geometric dimensioning and tolerancing (GTD) concepts. Additional examples of use of 3D printing in engineering education are provided in the comprehensive review by Eslahi *et al.* [6].

In this article, we describe new AM-driven design innovations created by a multidisciplinary team of undergraduate students at Tuskegee University, an HBCU institute, working on the development of a modular, multifunctional quadcopter drone [7]. This multiyear program is supported by NASA as part of an effort to improve the workforce pipeline for the aerospace industry, which is experiencing a shortage of talent, particularly given the projections of its future growth. The sector of Unmanned Aerial Vehicles (UAVs), generally referred you as drones, is fast growing and is expected to play a transformative role in the future of transport of people and commodities as well as delivery of services. The drone industry market size is expected to grow to $63.6 billion by 2025 [8] with the potential of creating large number of new jobs ranging from engineers to technicians, to professional drone pilots. Combining the interest of students in AM and in drone engineering creates unique opportunities for comprehensive design/manufacturing experiential learning allowing students to collaborate across disciplines covering the real-life product development cycle from ideation to the delivery of a market-worthy product. Compared to commercially available drones which have a fixed configuration and narrowly focused function, modular drones can be customized and configured for different missions and functions. Modularity can also allow drones to be quickly assembled, disassembled and compactly packed, a useful feature for remote missions. All those features make modular drone development more intellectually stimulating, challenging, and open-ended, which provides students with opportunities for design and manufacturing innovation. Several groups worked on the development of modular drones. Using AM, Murat *et al.* [9], developed a framework for mission-oriented parametric modular design and construction for fixed wing UAVs. Brischetto *et al.* [10] developed a multipurpose multirotor drone which can quickly change its configuration. At the center of their design, a universal body which has a circular ring to which arms of different configurations can be easily installed and angularly spaced. Hexadrone, [11], a French company, developed a modular quadcopter drone with four quick release arms. Another company, Clogworks Technologies [12], claims to have developed a drone with fully detachable arms and quick release payload attachment which is compatible with a wide range of payload options. Airblock [13], a modular educational drone kit, which can be easily assembled into drones of different configurations using magnetic attachments, was developed. Akasheh *et al.* [7], presented different modularity concepts for a quadcopter drone, including detachable drone arms which integrate electrical wiring for quick structural/electrical assembly to the drone body in a single step, optional propeller guard which can be quickly assembled/disassembled using snap fits into small parts that can be compactly packed, and customizable 3D-printed Power Distribution Board (PDB) replacing fixed configuration commercial PDB's, while allowing more flexibility in the design of the power distribution system of the drone.

In this article, we report on new results from the continued development work of the modular quadcopter drone performed by a multidisciplinary team of undergraduate engineering students, as described in [7]. We focus on the custom 3D-printed PDB concept reported there and present subsequent steps in its development process including additional iterations on the concept, testing of its function, and its ultimate integration into the drone design. In Section 2, we describe the project setup and mentoring approach. Section 3 describes the different stages of the AM-driven development process of the PDB, while Section 4 presents the results of a qualitative assessment based on surveys and focus groups, which were conducted by an independent external evaluator. Finally, we conclude and present future directions in Section 5.

2. Learning and Mentoring Framework

As mentioned in the Introduction, a main objective of this project is the better preparation and alignment of the engineering workforce training with the needs of the US aerospace manufacturing industry (and the manufacturing industry at large). Besides the core technical skills targeted under the project, AM and drone development, an equally important objective is that engineering graduates acquire a set of complementary skills highly valued by industry such as the ability to work effectively in interdisciplinary teams, leadership, time management, life-long learning, and entrepreneurship mind set. To achieve both objectives, we utilized the Vertically Integrated Projects (VIP) model for experiential learning to guide our learning-mentoring approach [14,15]. The VIP model relies on long-term, open-ended, and challenging research and development projects with multi-year participation from undergraduate students working on the different aspects of the project. Combined with close mentoring of experienced faculty and senior student participants, such learning-mentoring framework is expected to facilitate in-depth learning, innovation, and the attainment of a wide range of professional skills such as life-long learning, working in teams, communications, and leadership.

The details of our adoption of the VIP experiential learning model to the modular drone development project was detailed in a previous article [7]. Here, we highlight the main features and elaborate on the specifics as it relates to the development of the customizable PDB via AM, the focus of this article. Due to the multidisciplinary nature of this project, a team of students with suitable background and interests was assembled. Over the couple of years since the beginning of the project, students from mechanical, electrical, and aerospace engineering were assigned lead roles and responsibilities, along with an experienced faculty mentor, for different aspects of the drone development: structural design, computational aerodynamics analysis, manufacturing via AM, and avionics. Nevertheless, all students were intimately exposed to the work done in the other tracks as that was necessary to successfully complete the interconnected tasks. Such discipline crossing was not only a natural necessity but was also encouraged by the mentors and facilitated by the fact that students shared the same lab space where they did their work. Furthermore, to build self-confidence, promote life-long learning and develop leadership skills, the students were encouraged to take full ownership of the development process by giving them the latitude needed to find for themselves what works and what does not. Students were given enough independence to conceptualize ideas and solutions to increase the modularity and functionality of the quadcopter drone.

Following a systematic approach for addressing the drone modularity challenge, students were encouraged to follow the design thinking methodology [16], which is known to facilitate arriving at the kind of out-of-the box solutions needed for the open-ended modular drone development project. Following the first of the five steps of design thinking, *empathize*, students defined the stakeholders and potential applications of the modular drone, which in turn was used to *define* the design criteria and metrics. It is at this stage that the need to have a customizable 3D printed PDB was conceived driven by the limited sizes and configurations of commercially available PDB's. In the next step of the design thinking process, *ideate*, a conceptual design for the PDB was arrived after different ideas were considered through a brainstorming process. Once students agreed on a solution, *prototyping* followed in order to *test* the concept and to determine it can function as desired within the performance and safety considerations determine in the define phase. Normally, this phase requires several iterations as unforeseen issues with the design, manufacturing, and/or performance are identified. More details on the design thinking approach as it relates to the modular drone development project can be found in [7]. In what follows, the details of the development of the PDB, from conception to prototyping, to testing, and final integration in the drone system are presented.

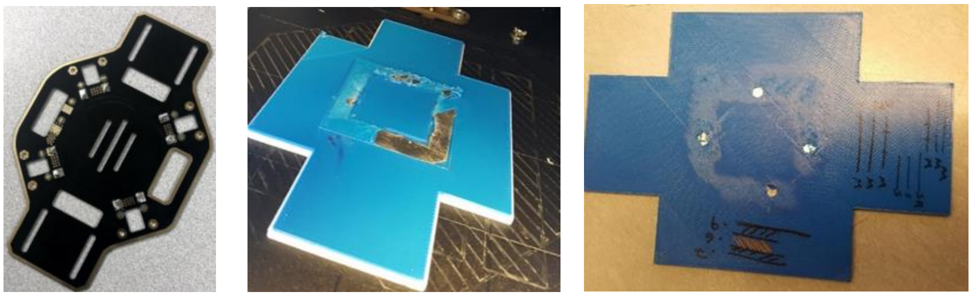
3. Development of Customizable 3D-Printed Power Distribution Board

In this section we present the process by which the customizable PDB is developed, prototyped and tested as part of the modular drone development project. This process is a good demonstration of the kind of design innovations that AM can enable due to its unique benefits, as described in the Introduction. The ability to produce parts with extremely complicated geometries in a time and cost feasible manner is key to such innovations. Furthermore, the ability to pause the part building process and place artifacts such as electric wiring and sensors, before resuming printing over and embedding, is another feature of AM facilitating the realization of innovative parts with multifunctional capabilities. The development of the customizable PDB described below is an example such design innovations which capitalizes on the unique advantages of AM. Reporting on embedding artifacts as related to drone development are scarce in literature. Using AM, Singapore Centre for 3D Printing [17] developed a 3D-printed drone with embedded electronics. In another work, electric wires were also embedded in plastic via fused deposition modelling (FDM) AM process using a modified nozzle which feeds the wire while heating it, resulting in a strong bond with the plastic [18].

Once the need for customizable PDB was identified, students went through several iterations before a final design and associated manufacturing plan was adopted. The next step in the development process consisted of testing the basic function of the PDB as well as additional testing to make sure that the temperature rise due to current flow can be tolerated by the ABS plastic used to build the board. Finally, the developed and tested concept was integrated in the drone system which, besides customization, offers the additional advantage of consolidating the drone body and the PDB. In what follows, we describe the different stages, including iterations, of the PDB development process mentioned above. It is worth mentioning that although the first two conceptual design iterations described here in Section 3.1 and 3.2.1 were developed and reported on in a previous work, [7], we chose to repeat them here for completion by providing the context and demonstrating the iterative nature of the product development cycle. All the models shown here were printed using Startasys UPrint SEplus FDM printer using their proprietary ABS plastic. This plastic is a copolymer which is designed to have higher strength than standard ABS used for FDM filaments.

3.1 Concept design 1: Embedding wiring during 3D-printing

The first PDB concept developed by the students was naturally similar to the commercial PDB used as part of the current drone electronics hardware, Figure 1a. To produce the board by AM, the concept of creating a cavity of desired shape that will house the electric conductor, pausing the printer at the right point, embedding the conductor, and resuming printing over was used [7,17]. Figure 1b shows a proof-of-concept plastic plate in which a conductor shaped like a rectangular ring has been embedded, and partially printed over, while Figure 1c shows the final product with the conductor completely embedded after completion of printing, except for a number of points which serve as electric connection node similar to the commercial PDB. Although successful, this procedure proved to be impractical with little tolerance to imperfectly flat conductor and the need for special attention to avoid collision between the printer nozzle and the conductor.



(a) (b) (c)

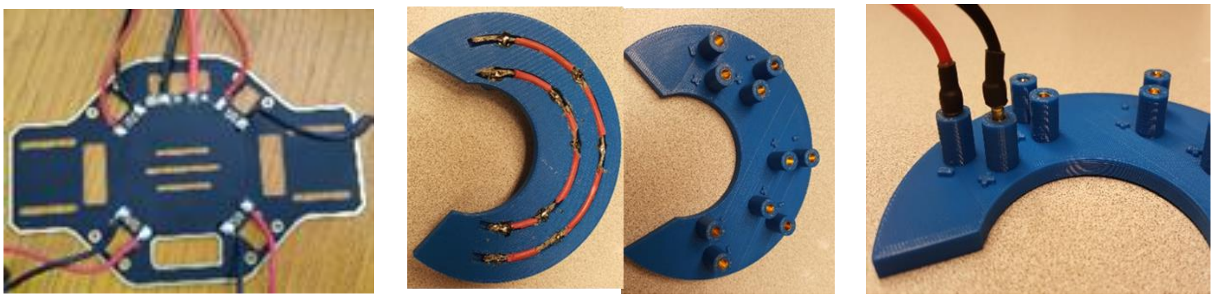
Figure 1: Concept demonstration of alternative 3D printed power distribution board via conductor embedding during printing, (a) original commercial board, (b) snapshot during printing, and (c) alternative board model completed [7]

3.2 Concept design 2: Embed wiring after printing- a two-part PDB design

The second design iteration aimed at circumventing the need to pause printing in order to embed electric wires consisted of making the board in two halves, top and bottom, with the bottom one housing the channels in which the wires will be routed [7]. Additionally, this design created the possibility of adding design features to the top half of the board that enable embedding bullet connectors and establishing an easy way to connect the motor wires, instead of relying on standard soldering of motor wires at the PDB nodes, Figure 2 a and c. This represents a significant boost to modularity as the replacement of drone arms can now be done quickly and easily performed without the need for soldering. Two different designs of the two-part PDB board were attempted. In the first attempt, the bullet connectors were fully immersed in the top half, while in the second attempt, the bullet connectors were partially embedded, which resulted in significant simplification of the soldering process.

3.2.1 Two-part design with fully immersed bullet connectors

In this two-part design, the bottom half is furnished with a groove where electric wires are placed. The top half, where bullet connectors are fully embedded at the power distribution nodes, assembles with the bottom half creating the board, Figure 2 b. To connect the electric wires to the bullet connectors, soldering the electric wire to the bottom of embedded bullet connector presented a challenge due to the need to remove the insulating sheath and the creation of a deep junction by soldering.

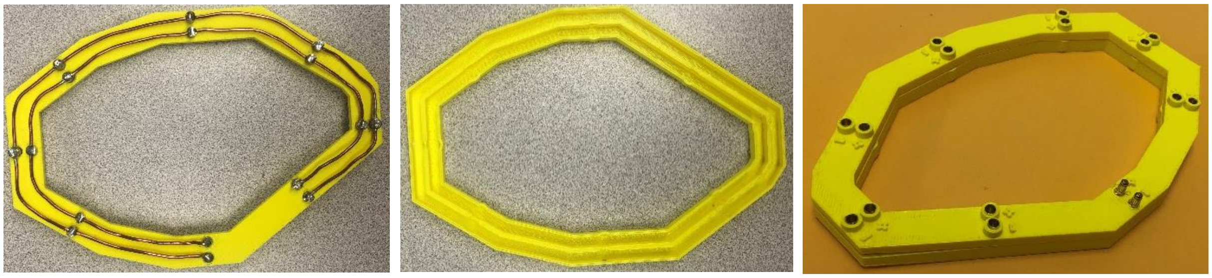


(a) (b) (c)

Figure 2, (a) connecting drone motor wires via soldering in the case of the commercial PDB, and (b) customizable two-part PDB design with fully immersed bullet connectors, and (c) connecting drone motors via embedded bullet connectors in the case of our PDB design [7]

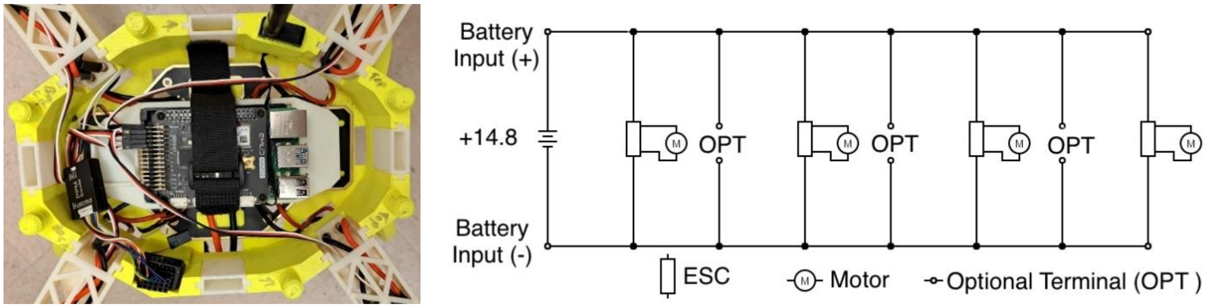
3.2.2 Two-part design with partially immersed bullet connectors

To overcome the difficulty with soldering the wires to the fully immersed bullet connector as described in Section 3.2.1, a slightly modified design with the bottom of the bullet connector exposed resulted in a much simpler soldering process, Figure 3. Since this design will be the one to adopt for further development, its prototype was made more compatible with the actual design on the drone body where it will be installed. Figure 4 shows a top view of the current design of the drone body which the PBD is designed for. As can been seen, besides the four “outlets” needed to power the four drone arms, battery input inlet and three additional power outlets are available for optional utilities. When not in use, these outlets can be covered, as seen by the dummy plugs in Figure 4a. Figure 4b shows the corresponding circuit diagram of the power systems of the drone.



(a) (b) (c)

Figure 3, working model of our in-house power distribution board, (a) the bottom side of the top half showing the solid copper wire soldered to the connecting nodes, (b) the top side of the bottom half showing the groove in which the copper wire would sit upon assembly, and (c) the power distribution board after assembly.

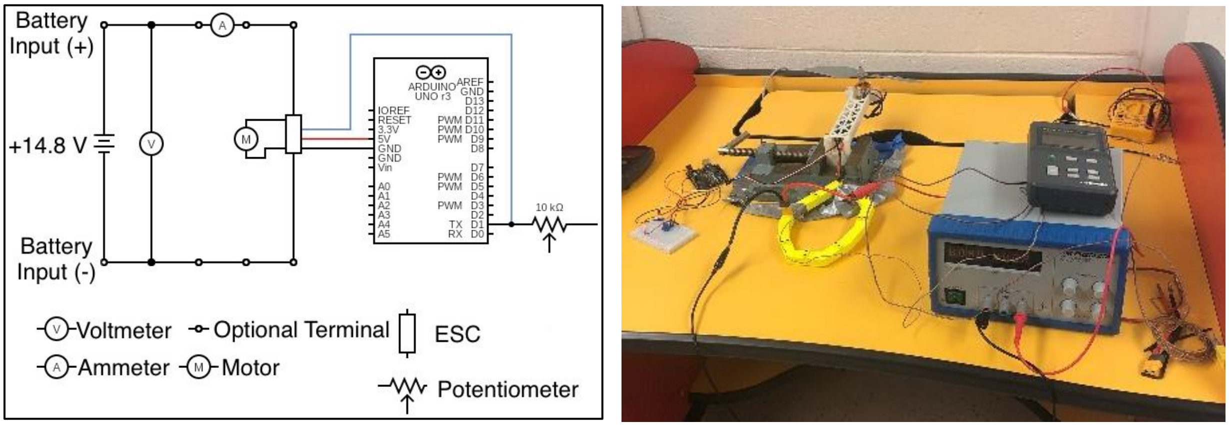


(a) (b)

Figure 4, (a) the current revised design of the drone body, and (b) circuit diagram of the PDB showing four branches that power the four drone arms' motor/electronic speed controller and three optional outlets

3.3 Function Testing of PDB

After the conceptual design in adopted, the next step towards developing this concept into a working model is to test the function of PDB. The basic electric connectivity between the main power node and the utility (distribution) nodes was tested and verified to reflect the circuit design. Another important operational consideration is the heating of the board due the high current it delivers from the battery to the motors- through the electronic speed controllers (ESC)- and other utilities. With guidance from the electrical engineering faculty mentor, student with mechanical engineering background set up a test to monitor the temperature at a representative location on the power distribution board. The setup, shown in Figure 5, included one motor complete with the propeller and speed controller, an Arduino Uno, 15V/5A power supply, potentiometer (to provide the control signal normally provided by the flight controller during drone flight), voltmeter, ammeter, miscellaneous wires, breadboard, and a thermocouple/data logger. The power supply voltage and potentiometer setting are fixed during the test, while time, temperature, and current (which is controlled by the potentiometer) are recorded. Preliminary results show that the increase in temperature over the 30-minute estimated normal continuous flight time of the drone before the battery is depleted, at an average operating current of 5A is about 10 ^{o}F and no more than 18 ^{o}F if the flight duration is increased to 60 minutes, Figure 6. As such, the conclusion from the test data indicates that the PDB does not present a risk of overheating at the tested operating conditions. Additional testing is needed at current levels representative of the highest anticipated loads. This was not possible due to limitations of available power sources.



(a) (b)

Figure 5, set up to test the heating of the PDB, (a) the circuit diagram of the test set up, and (b) the actual setup showing the drone arm, temperature logger, power supply potentiometer and the PDB

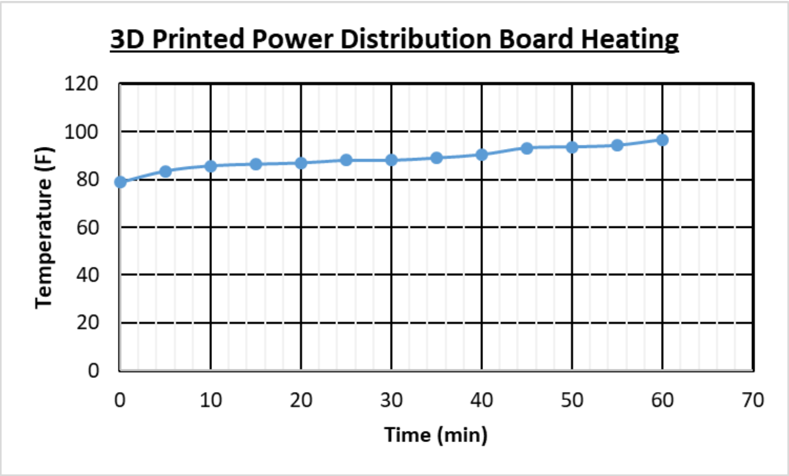


Figure 6, temperature as a function of time during the operation of the power distribution board

3.4 Integration of the PDB into the drone design

The final step in the development of the PDB is to integrate it into the drone design. Although the developed PDB can be used as a separate component, just as in the case of the commercial PDB, integrating it directly into the drone design would offer the additional advantage of part consolidation, another advantage of AM to capitalize on, Figure 7. Figure 7b shows the electric wires' placement in a dedicated recess in the bottom side of the drone body. Apparent there is the soldered junctions between the wires and the female bullet connectors embedded in the drone body. Figure 7a shows the top view of the drone body with the embedded bullet connectors. To protect the electric wires, a cover of the same shape as that of the recess is separately designed and 3D printed, such that it fits tightly into the recess. The cover is secured in place through a separate assembly step after the drone body and cover have been printed the wires placed.

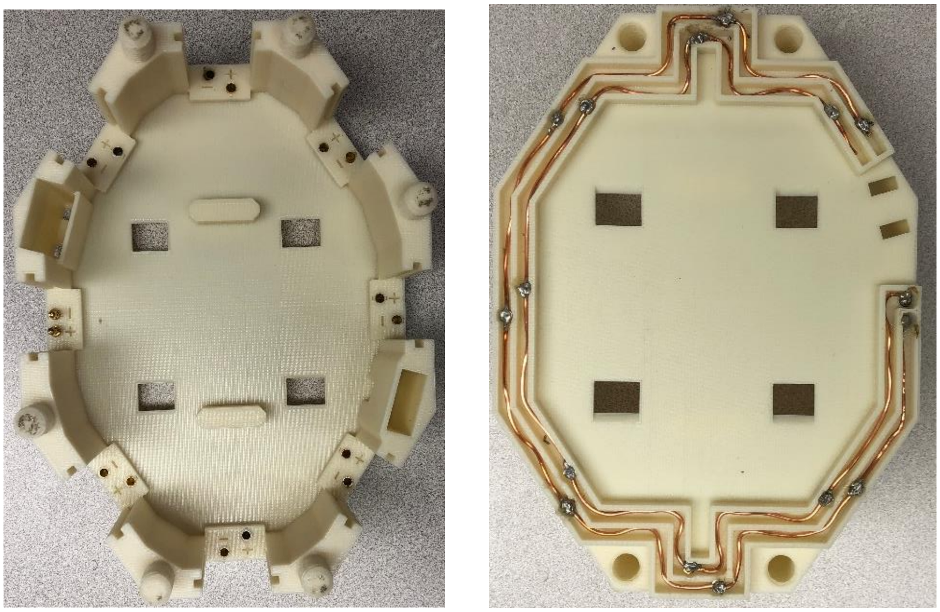


Figure 7, integration of the developed PDB into the drone body design, (a) top view of the drone body showing the battery input node (far left) and the seven outlets (four for the quadcopter morors and three optional outlets as needed), and (b) bottom view of the drone body with the electric wires routed and soldered to the different outlets (a lid will cover the wires in the fully assembled drone)

4. Assessment of the program outcomes

As part of the evaluation of the project, we previously reported on the findings of an external evaluator regarding students' experiences and attainment of the desired learning outcomes and skills during the first year of the project, academic year 2021/2022, [7]. Given the small sample size, a structured focus group consisting of all six engineering students from different disciplines who participated in the project (the whole population) was conducted by the evaluator to gather feedback and descriptive data. While keeping in mind the small population size constrained by the nature of the project, the findings indicated positive students' experiences and learning outcomes. Students highlighted the gained understanding of AM and the role it can play in product development, interdisciplinary exposure, learning from each other's prospective, the opportunity to apply what they learn in classroom, improvement in their communication skills, and better readiness for their future careers. They also valued the independence and ownership they were given, combined with the close and constant interactions with their mentors.

Besides the focus group, data was gathered through surveys during Spring 2022 from all six participants who participated in the focus group described above, as well as from four participants who worked on the project beyond Spring 2022 until the date of collection of this data in Spring 2023. Two of the four students were returning students, while the other two were new to the project. Finally, two of the six students surveyed in Spring 2022 graduated and went on to pursue engineering career in corporate America in one case and graduate degree in engineering in the other. Those two graduates were also surveyed late in Fall 2022. The survey, which were administrated anonymously by the same independent external evaluator, included closed response items and scales as well as focused open-ended questions. More specifically, students were asked to indicate their confidence in meeting program objectives or perceived benefits of their involvement, perceived project outcomes, confidence in their 21st century skills (e.g., leadership, collaboration), persistence, preparation for jobs and careers and overall career readiness. Items on each of these areas were measured using a 5-point response scale, where 5 indicates strong favorable agreement and 1 indicates strong unfavorable disagreement. To reiterate, three surveys were administrated between spring semester 2022 and spring semester 2023. The initial and final surveys included all participating students (n=6 in Spring 2022, n=4 in Spring 2023), while the survey of graduates (n=2) was administered in Fall 2022. Table 1 summarizes the survey results of this assessment scheme. Overall responses were very positive with all scales averaging above 3.5, and 5 of the 6 areas averaging above 4.0 on both administrations. In terms of perceived project benefits, 21st century skills and persistence, average responses were higher in 2023 when compared to the previous year. When program graduates were surveyed in the fall, their responses also averaged slightly higher that the overall pool of participants did in spring semester 2022.

	Participants (n=6) Spring 2022	**Graduates (n=2) Fall 2022**	**Participants (n=4) Spring 2023**
Scale	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**
Perceived Benefits	4.57 (0.328)	4.58 (0.378)	4.72 (0.253)
Project Outcomes	3.62 (0.691)	3.80 (1.13)	3.60 (0.844)
21st Century Skills	4.80 (0.186)	NA	4.84 (0.187)
Persistence	4.14 (0.427)	NA	4.46 (0.534)
Career/Job Prep Skills	4.52 (0.338)	4.56 (0.379)	4.33 (0.237)
Career Readiness	4.65 (0.224)	NA	4.47 (0.503)

Table 1, Summary of independent evaluator survey findings based on 5-point scale, with 5 indicating strong favorable opinion.

Year 1 and Year 2 Comparisons- As a follow-up to the overall scales summarized in Table 1, more detailed comparisons were made between the groups of students participating in year 1 (spring 2022) and year 2 (spring 2023). These comparisons were made for the specific items that are aligned with each scale. While these comparisons were for all participants from each year, sample sizes were too small for meaningful statistical analysis. The following sections offer a descriptive comparison between year 1 (2022) and year 2 (2023) participants of specific items related to student's perceived project outcomes, confidence in their 21st century skills, and preparation for jobs and careers. The other items tell a similar story and we do not share them here, nor the specific question under each item, for length considerations.

Participant Perceived Benefits - Students were asked to review a series of statements related to project activities, objectives and expected benefits as a result of their involvement. Students from each year expressed very positive beliefs related to their participation with all items averaging above 4.0 and 19 items out 28 above 4.5 in 2022 and 25 of 28 above 4.5 in 2023. In addition, 20 of the 28 items received more positive responses in 2023 when compared to 2022. Areas in which students in 2023 were more likely to indicate improvement included entrepreneurship skills, additive manufacturing, product development skills, technical skills, project management skills, internship, job and career preparation and lifelong learning abilities.

21st Century Skills – Because of the collaborative and problem-solving focus of this project, students were asked to indicate their level of confidence in skills related to setting and accomplishing goals, teamwork, time management and working with others from different disciplines or backgrounds. Students were very confident in these skills with all 11 items averaging above 4.0 both years. In addition, students in year 2 (2023) reported equal or higher levels of confidence for 9 of the 11 questions used to assess those skills. Students most strongly agreed that they were confident in terms in their ability to produce high quality work, respect differences of their peers, include other's perspectives when making decisions, and working with students from different backgrounds.

Preparation of a Job and Career – Students were asked to indicate the extent to which they were confident they had the skills necessary to get a job and pursue a career. They were very confident with all responses averaging 3.5 or above in both 2022 and 2023. Students were especially confident in their leadership ability (M=4.6 in 2022 and M=4.67 in 2023), cultural awareness (M=4.8 in 2022 and M=4.67 in 2023), curiosity and persistent desire for continuous learning (M=4.8 in 2022 and M=4.67 in 2023), and research and evaluation skills (M=4.6 in 2022 and M=4.67 in 2023).

5. Conclusion and future work

In this work, we have shown that AM can be a powerful tool providing unique opportunities for engineering students, not only to quickly and feasibly realize their conceived designs but also to open the doors widely for creativity and innovations not possible otherwise. To maximize those benefits, a challenging project requiring out-of-the-box solutions that open-ended should be selected. To the extent possible, students should also advance to the later stages of the product development process, where testing and certification are considered. An experiential learning setup with structures that promote independence and meaningful student interactions across disciplines, not only with other students involved in the project, but also with mentors who are available to closely interact with them, can play an important role in students' attainment of both technical and non-technical skills. Skills such as communication, teamwork, entrepreneurship, time management, and leadership are critical for success in today's work environment, making them highly-valued by industry. Although the sample assessed by the evaluator consisted of the whole population, it remains small and additional data collection over several years is desirable to confirm the positive learning outcomes. In future work, additional testing of PDB at more demanding conditions is needed followed by test flying the drone body integrating the PDB.

Acknowledgment

The authors would like to acknowledge the direct financial support of NASA's Minority University Research and Education Project (MUREP) under cooperative agreement number 80NSSC20M0013. The authors also thank Chevron for its support to our manufacturing infrastructure.

References

[1] Transformation In 3D: How A Walnut-Sized Part Changed The Way GE Aviation Builds Jet Engines. (2018, November 19). *GE*. https://www.ge.com/news/reports/transformation-3d-walnut-sized-part-changed-way-ge-aviation-builds-jet-engines

[2] *Grand View Research*, "3D Printing Metal Market, 2021-2028", Report ID 4751756, October 2021

[3] G. Tipker, G. Golub, M. Dube, C. Tejesh and J. Zhang, Jing, "Integration of 3-D Printed Drone Project in General Engineering Curriculum", *American Society of Engineering Education, 126th Annual Conference and Exposition*, 2019, Paper ID # 27759.

[4] B. Hur, D. Malawey, J. Morgan and C. Ma, "3-D Printed Metal and Plastic Propeller Design and Manufacturing for Smallscale, Underwater Thrusters", *American Society of Engineering Education, 126th Annual Conference and Exposition*, 2019, Paper ID #26855

[5] O. Rios "Teaching Geometric Dimensioning and Tolerancing Concepts Using 3-D Computer Models and 3-D Printed Parts", *American Society of Engineering Education, 125th Annual Conference and Exposition*, 2018, Paper ID # 21827.

[6] Eslahi, A., Chadeesingh, D.R., Foreman, C., Alpay, E. (2020). 3D Printers in Engineering Education. In: Gravett, K., Yakovchuk, N., Kinchin, I. (eds) Enhancing Student-Centred

Teaching in Higher Education. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-35396-4_7

[7] F. Akasheh, M. Ndoye, D. Shannon, R. Pippins, E. Thompson, A. Carter, S. Baker, and B. Guiseppi. "Additive Manufacturing-Enabled Modular Drone Design Development by Multidisciplinary Engineering Student Team." In *2022 ASEE Annual Conference & Exposition*. 2022, Paper ID #38111

[8] Drone market outlook in 2023: industry growth trends, market stats and forecast. *Business Insider*. https://www.businessinsider.com/drone-industry-analysis-market-trends-growth-forecasts.

[9] Bronz, Murat, Ezra Tal, Federico Favalli, and Sertac Karaman. "Mission-oriented additive manufacturing of modular mini-UAVs." In *AIAA Scitech 2020 Forum*, p. 0064. 2020.

[10] Brischetto, Salvatore, Alessandro Ciano, and Carlo Giovanni Ferro. "A multipurpose modular drone with adjustable arms produced via the FDM additive manufacturing process." *Curved and Layered Structures* 3, no. 1 (2016).

[11] Hexadrone. Tundra. https://tundra.hexadrone.fr/ (accessed on 20 February 2022).

[12] Clogworks. Dark Matter. https://www.clogworks.com/ (accessed on 20 February 2022).

[13] Kickstarter. Airblock. https://www.kickstarter.com/projects/makeblock/airblock-dron

[14] Strachan, Scott Munro, et al. "Using Vertically Integrated Projects to embed research-based education for sustainable development in undergraduate curricula." *International Journal of Sustainability in Higher Education* (2019).

[15] E. Coyle, M. Stephen, D. Brigita, E. Maria, and I. Smith. "Linking research, education, and professional skills: vertically integrated projects at 4 institutions." In *2021 European Learning & Teaching Forum*. 2021.

[16] Cross, Nigel. *Design thinking: Understanding how designers think and work*. Berg, 2011.

[17] 3D Printing & Embedded Electronics – How AM Enables Smarter Objects. 3DPrinting.com. https://3dprinting.com/3d-printing-use-cases/3d-printing-embedded-electronics/

[18] J. Bayless, M. Chen, and B. Dai. “Wire embedding 3D printer”. *Engineering Physics Department,* University of British Columbia, 2010