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Additive Manufacturing-Enabled Modular Drone Design Development by Multidisciplinary Engineering Student Team

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Additive Manufacturing-Enabled Modular Quadcopter Drone Design Development by Multidisciplinary Engineering Student Team

Abstract

Additive manufacturing (AM) is recognized as a transformative approach to prototyping and manufacturing by all sectors of industry, especially the aerospace industry, which has lead the adoption of AM for critical end use parts. In academia, AM has also received great deal of interest as a vehicle to improve design and manufacturing education and facilitate student innovation. The objective of this effort is to improve the readiness and diversity of the engineering workforce in the aerospace industry, which is experiencing critical scarcity in talent. We engaged a multidisciplinary team of minority engineering students in the design and manufacture of a modular quadcopter drone driven by AM. The modular drone focus provides a suitable context for the implementation of experiential learning, which is proven to support the development of practical student research and engineering design skills. Design thinking was used to drive the developments needed to achieve a modular drone that can be easily customized and reconfigured for different applications. With the design flexibility offered by AM, students designed and built drone arms that can be quickly detached and assembled, both structurally and electrically in one-step while avoiding the need for soldering electric connections at nodes. They also developed an optional propeller guard, which can be compactly packed, if not needed, as well as a concept for a 3D printed power distribution board to replace standard commercially available boards. An additional objective of the project is to arm students with desirable soft skills such as interdisciplinary team skills, leadership, lifelong learning, and entrepreneurship mind set. To guide students in this project, a multidisciplinary team of faculty mentors met with the student team once a week to advice on technical issues and provide general direction and context. The students' work schedules were deliberately selected to maximize overlap between team members with the aim of facilitating effective communication and cross-disciplinary exchange of ideas. Furthermore, to build self-confidence, promote experiential 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. Through a focus group with the participating students, an independent external evaluator found that the project context and mentoring approaches helped them experience the benefits of AM, improved their understanding of real-life engineering product development as well as their engineering courses. It also helped them better understand entrepreneurship and the importance of effective communications and leadership.

1. Introduction

1.1. Additive Manufacturing

In recent years, additive manufacturing (AM), also known as 3D printing, has received a great deal of interest from different industries as well as academia due to its demonstrated potential to transform the way prototypes, functional models and end parts are fabricated. 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% [1]. AM evolved from rapid prototyping techniques, which have been in existence since the 1970's. Advancement in 3D printing technologies and materials, combined with expiration of key technology patents in the early 2000's led to the accelerated transition of rapid prototyping techniques into a viable manufacturing process for more sophisticated conceptual prototypes, functional prototypes, and end use parts. Starting from the CAD model of a part, AM workflow starts by slicing the model into 2D layers of small thickness followed by creating the part layer by layer using different forms of material and different technologies to consolidate it [2]. ASTM classifies AM processes into seven categories: material extrusion, vat polymerization, material jetting, binder jetting, powder bed fusion, direct energy deposition, and sheet lamination [3]. The most accessible of those technologies (also used in this work) is material extrusion of thermoplastic filament, typically referred to as fused deposition modeling (FDM). Advantages of AM include the ability to create complex geometries and part consolidations, which are not possible or not feasibly achieved using traditional manufacturing approaches. Because molds and dies are not needed to build parts, AM can offer significant reduction in lead time and production cost of parts. This is particularly the case when one-of-kind parts or low-volume production is needed. Another advantage of AM is the ability to facilitate vertical integration within an enterprise. In addition to expediting product development, the AM framework facilitates the development of innovative products of higher value, which can offer a competitive advantage over standard low-cost products. One of the lead adaptors of AM for end parts is the aerospace industry due to the high added value of AM-enabled innovative parts. A prominent example of the adoption of AM for critical flight parts is the leap engine fuel nozzle developed by General Electric [4]. The original nozzle consisting of 19 parts was redesigned with more intricate fuel channels leading to improved ignition efficiency of 25% while consolidating the assembly into a single part.

A main objective of this work is to train engineering students in AM and its application in the aerospace industry, more specifically, the nascent field of drone engineering and operations. Drones, more generally known as unmanned aerial vehicles (UAVs), are flying vehicles which can be controlled at different levels ranging from remote piloting by a human to full autonomous operation where the vehicle can make decisions on its own, e.g., collision avoidance and/or return-to-home. Originally developed for military operations, drones are nowadays enthusiastically adopted by many groups and industries for recreation, photography, delivery, surveillance, agriculture, to name a few applications. The drone industry is fast growing and expected to have a major economical and development impact in the near future, including the potential of creating large number of new jobs ranging from engineers, technicians to professional drone pilots. According to the Insider Intelligence, the market size of the drone services market is expected to grow to $63.6 billion by 2025 [5]. This excitement about drones, combined with the relative simplicity of basic drones, has created interest in drone engineering in undergraduate engineering as well as STEM outreach programs.

1.2. Significance of AM in supporting workforce development in academia

In higher education institutions, AM is increasingly utilized as a tool to enhance design and manufacturing education and to empower students to innovate and quickly realize their ideas. Students can design, manufacture, validate, and continuously iterate their designs in a relatively easy and quick manner until they achieve the desired design outcome. Over the course of this process, students gain practical understanding of AM processes and how to design for them, a skill that is urgently needed to accelerate the adoption of AM in industry. AM-based projects also help students learn how to work in teams, another highly valued skill in real-world product development operations. By collaborating in sub-teams focusing on design, manufacturing and inspection, students also learn early on that effective communication during the design phase is crucial for effective product development to avoid pitfalls and expensive time-consuming fixes later during the manufacturing, inspection, and end use phases. Students engaged in design activities learn about the capabilities and limitations of the different AM processes, while students focusing on manufacturing tasks learn how to capture the designer's intention based on their understanding of the relationship between the part quality and performance, and the AM processing parameters such as the build orientation or the infill parameters.

Several examples of integration of AM and drones in engineering education can be found in literature. For example, Hur *et al.* demonstrated the use of metal and plastic AM in a senior capstone project setting to design and fabricate propellers for small-scale thrusters for underwater robots [6]. Through that process, students gained first-hand experience around critical issues such as support design, part warp, and overhang constraints. Tipker *et al.* combined 3D printing with unmanned vehicles in freshman engineering class. Students were presented with basic drone electronics kit and were asked to design and 3D-print a suitable drone structure, assemble the drone, and fly it [7]. Jovanovic et al. used drones to expose high school students to the use of drones in geospatial technology and rescue operations [8]. Finally, Rios [9] used 3D CAD models and corresponding 3D-printed parts made by Fused-Deposition Modeling (FDM) to illustrate several geometric dimensioning and tolerancing (GTD) concepts.

A recent solicitation by NASA's Office of STEM Engagement in collaboration with the Aeronautics Research Mission Directorate, High Volume Aerospace Manufacturing and Supply Chain Management, highlighted the urgent need to enhance the competitiveness of the US aerospace industry by aligning workforce training with the current needs of the industry. Building on the technological and education significance of AM and drone engineering, combined with the support of NASA, we engaged a multidisciplinary team of engineering students at Tuskegee University in a multi-semester modular drone development project based on AM as an enabler of innovative design and manufacturing. In addition to training and developing students in technical areas, this program is designed to equip students with a variety of skills that are highly valued by the aerospace industry (and industry in general), namely, interdisciplinary team skills, leadership, lifelong learning, design thinking, and entrepreneurship mind set.

The educational research that underpins the activities of this project is experiential learning and its demonstrated positive in skills and confidence building for underrepresented engineering students. A recent large-scale project (involving 13 HBCU engineering departments) reported very positive outcomes of experiential learning [19]. The activities of our project can be viewed as a case-study to qualitatively evaluate an experiential learning framework whose implementation and adoption can lead to the development of practical student research and engineering design skills and thus supporting our objective of improving the alignment and increasing the diversity of workforce in the aerospace industry.

The paper is organized as follows. In Section 2, we present the team set up and mentoring approach device to achieve the learning outcomes. Section 3 describes the different design innovations created by the students. Section 4 presents a qualitative assessment of students' perception of the efficacy of the program performed by an independent evaluator. Finally, in Section 5, we conclude and present future directions for this initiative.

2. Learning and Mentoring Environment and Design Framework

To achieve the objective of the project, our learning and mentoring environment is set up following the Vertically Integrated Projects (VIP) model [10], [11], which is a learning framework that operates in a research and development context. In VIP projects students are encouraged to participate for several semesters. This continuity favors technical depth, and disciplinary breadth by enabling the completion of projects that are of significant benefit to students' learning experience. The long-term, highly mentored, and technically challenging nature of projects provides undergraduates with an educational experience that fosters the creation of innovative ideas and the development of advanced skills. It has been shown that the VIP model presents many benefits such as, among others, improvement of student learning outcomes in both disciplinary and professional skills, better understanding of the innovation and research process, realistic team experience, opportunity to learn a varied set of skills, deeper practical experience in field of study, and development of professional skills: communication, leadership, and management [11].

Using the VIP model, we formed a multidisciplinary team of aerospace, electrical, and mechanical undergraduate engineering students. Students were given specific roles and responsibilities that fall into three main areas of the drone development process: (1) structural/aerodynamic design, (2) electronics systems integration and (3) manufacturing. Each of these sub-teams is assigned to a faculty mentor that has the most experience in the associated area. For example, an electrical/computer engineering faculty is the lead-mentor for students working on electronics and system integration while a mechanical engineering faculty supervises the students in the manufacturing sub-team. Nevertheless, all the team members (students and faculty advisors) meet once a week for updates and cross-advising. Faculty-mentors provide the minimal requisite direction and guidance to the students such that the undergraduate researchers have enough independence to conceptualize, realize, test, and reiterate on their various design solutions. To teach through experience that a key quality of problem solvers is the ability to learn from failure, students were given the latitude needed to find for themselves what works and what does not (even if foreseen by the faculty mentors).

The project typically involves six students during a given semester: i.e., on average two students per sub-team. Since an important objective of our initiative is for students to develop hands-on engineering design and research skills, participating students work in the laboratory (whenever possible) and maintain a 10 hour-a-week work schedule during the academic year. The students' work schedules in the laboratory are designed such that there are overlaps; thus, there is ample opportunity for students working on different parts of the projects to communicate and share ideas. Furthermore, Microsoft Teams platform was used to facilitate constant/daily communication and content sharing among students and between students and advisors. Another goal of the project is to promote life-long learning and exploration of new areas. Because lower-level (and even upper-level) students have no previous experience in requisite practical skills like electrical/electronic systems of drones or moderately complex CAD design, the faculty identify and provide access to onramp tutorials. For example, for drone electronics and design, the faculty mentors guided new participating students through an online drone course, which covers the basics and then leads then through the complete assembly, calibration, and flying of a quadcopter drone using a complete DIY package, which includes the structure, power train and electronic parts of drone. Through this approach, students learn through scaffolding and then transfer their knowledge when they are working on the in-house modular drone.

The overall assignment of the participating students was to design, build and fly a modular drone with the key functional requirements of easy and quick replacement of parts (for repair or function switching), configurable geometry and the ability to be customized. An additional requirement is that the drone be designed for and fabricated by AM to the extent possible to take advantage of the ability of AM to promote innovative product development. In contrast to fixed drone platforms available commercially, the development of a multifunctional modular drone using AM presents a challenge but also an opportunity to for design and manufacturing innovation. Based on our research, modular drone development efforts are limited and recent. In 2018, *Hexadrone*, a French company, developed a modular drone with 4 quick release arms allowing for quick assembly. Additionally, the drone body frame was 3D printed using fiber reinforced nylon via powder bed fusion technology [12]. Another company, *Clogworks* Technologies, claim to have developed a drone with fully detachable arms and quick release payload attachment to ensure compatibility with a wide range of payload options [13]. The last example identified is the *Airblock*, an educational modular kit, which can be easily assembled into drones of different configurations using magnetic attachments [14]

To take a principled approach to tackling the main design challenges, students were strongly encouraged to utilize the Design Thinking methodology [15], which has been shown to be quite effective in providing “outside-the-box” solutions to challenging problems. Roughly, the five processes of the Design Thinking methodology, shown below in Figure 1, were applied here as follows:

Empathize: Students will communicate with the faculty mentor and other stakeholders to gain even deeper insights into the prospective usage and the actual needs for a given system component (e.g., propeller guard)

Define: The additional information gathered during the *Empathize* phase helps the students identify the most critical performance metrics and design constraints.

Ideate: The students use a variety of ideation techniques of their choice (e.g., Brainstorm, Worst Possible Idea) to find the best way to approach the most critical issues.

Prototype: Once students agree on viable design solutions, they use the 3D printing in our Chevron Additive Manufacturing Lab to build various prototypes that implement the team's ideas.

Test: Students evaluate the performance of the prototypes against the outlined design objectives

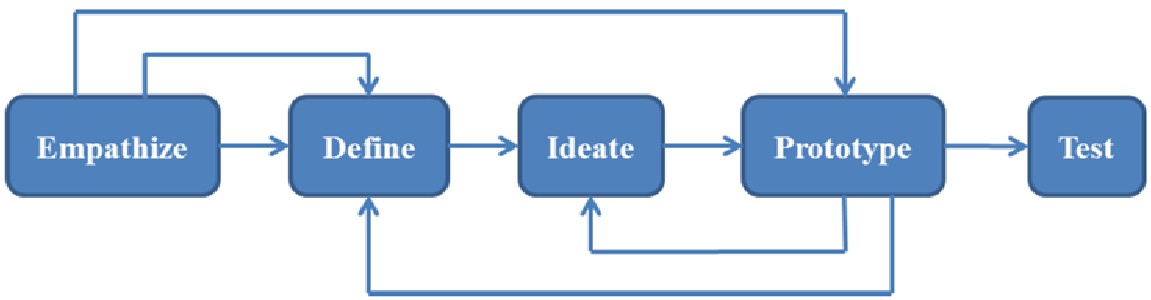


Figure 1: Stages of the Design Thinking methodology used to create the various design solutions

As seen in Figure1, the Design Thinking process may continue iteratively in a non-linear fashion until the team arrives at their most optimal solution with respect to the core design objectives. In each iteration, designs are continuously improved and/or new features are added.

Overall, we have observed that the learning and mentoring environment and the utilization of a principled design framework has enabled us to achieve the desired objectives and thus should enhance the preparedness of the participating students for the industry, especially the aerospace industry.

3. Modular drone development via AM

Based on the design thinking exercise performed by the students at the beginning of the project, they come up with several design criteria and features to implement in order to meet the design requirements, including:

1. detachable drone arms that enable quick assembly/disassembly of the arms for packing and replacement purposes.
2. Integrated structural/electrical assembly of the drone arm/motors. Normally, drone motors are connected to the power distribution board nodes by soldering. Avoiding the need for soldering, allows for faster and more convenient electrification of the motors, which is particularly important when the drone is operating in remote areas with no access to proper facilities.
3. Optional propeller guard, which can assembled/disassembled easily and packed compactly.
4. Customized 3D-printed power distribution board

In what follows, we discuss the developments of these design concepts. Figure 2 shows a picture of the current version of the modular drone assembled. The drone has a total weight of 5.8 lb, propeller diameter of 14 in, and body dimensions of 8.5x7.0 in. All fabricated parts shown were 3D- printed using ABS on an FDM printer (UPrint-SE plus from Stratasys). The modular drone development combined with AM provides unique educational experiences. Modular drone design presents different technical challenges from those found in typical drones with fixed configuration. Students working on this project had ample opportunities to innovate in different aspects of the modular drone including functionality, design, and manufacturing as detailed below.

Figure 2: Picture of the current version of the drone developed by the students. The drone weighs 5.8 lb and has overall dimensions-including the arms- of 14x14in

3.1 Detachable drone arms

The idea behind the detachable arm is to allow quick disassembly/assembly of drone arms as needed. This could be for replacement or repair purposes or for switching installed arms with different types of arms to enable new functions/capabilities. Commercially available small and medium size drones, normally exhibit arms which are either structurally integrated into the drone body or fastened in a way that does not allow for quick or easy assemble/disassembly. The design developed by the students involved a vertically sliding fit. To secure the arm from sliding out under the effect of thrust forces, the design relied on the drone body cover, which slides in place horizontally and is secured by the recess in the drone body, Figure 3.

(a) (b) (c)

Figure 3: Detachable arm design based on sliding fit, (a) and (b) show the groove where the arm assembles and the recess where the cover slides preventing the arms from sliding out during flight, and (c) drone arm assembled to the body

3.2 Integrated structural/electrical assembly of drone arms

While the concept of quick assembly and disassembly of drone arms presented above accomplishes the desired objective of fast attachment, the full benefit of shortening the time to be back in flight is not achieved. To power the motor after the arm is structurally assembled, the common practice entails soldering the speed controllers' wires (motor is connected to the power distribution board through a speed controller) to the power distribution board as shown in Figure 4.

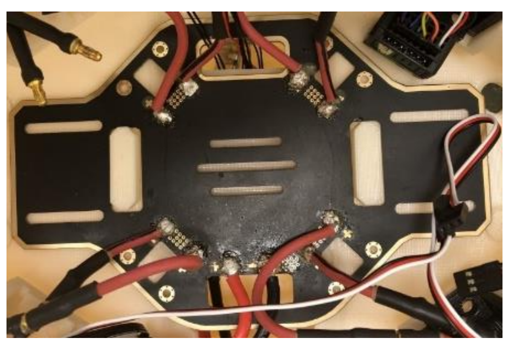
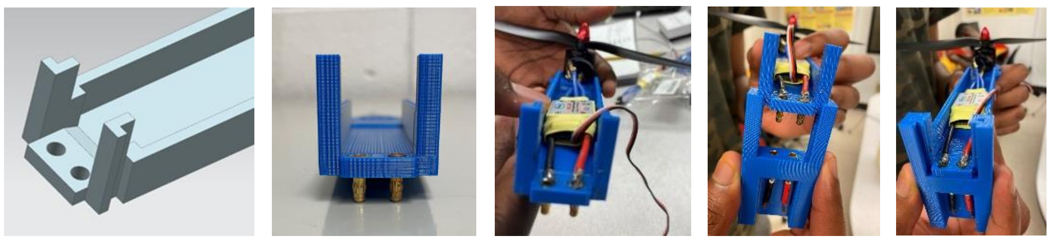


Figure 4: commercial power distribution board with electric wires soldered at the nodes

Besides requiring additional time, soldering requires certain conditions and specific tools, which might not be available when operating the drone in remote fields. Therefore, it is desirable to avoid soldering. To overcome this impediment, the students' solution consisted of integrating electric and structural connectivity into one step. The arm design was modified to allow embedding male bullet connectors at the end of the arm, Figure 5 a-c. Corresponding to those male connectors, female connectors are embedded in the drone body frame, which are in turn connected to the power distribution board. As the arm slides to attach to the body, the corresponding bullet connectors simultaneously engage, establishing the electrical connection, Figure 5 d and e (to save on unnecessary materials usage, Figure 5d and e show a representative model of the part of the drone body involved in the assembly). Several designs of embedded bullet connectors to create customized 3D printed plugs and connectors are available [16]. This empowerment of designers to quickly and cheaply prototype and test novel concepts is an example of the key benefits of AM in the product development stage.



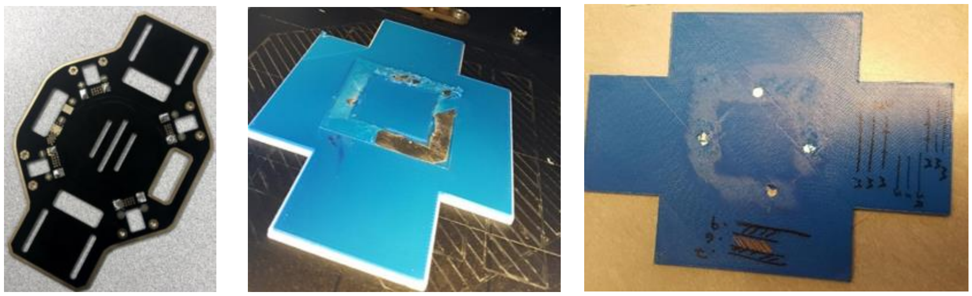
(a) (b) (c) (d) (e)

Figure 5: modified drone arm integrating structural and electrical assembly, (a) CAD model showing holes for inserting male bullet connectors, (b) and (c) 3D printed arm with connecters inserted and ESC wires soldered, (d) and (e) arm assembly to a the drone body frame model

3.3 Customizable 3D printed power distribution board

One of the design and manufacturing innovations enabled by the geometric complexity and incremental layer-by-layer building of a part by AM, is the concept of embedding of artifacts in parts. By creating an internal cavity of desired geometry and pausing the printing process at the proper time during printing, developers can embed sensors, electrical conductors, tags etc. Using FDM technology, Singapore Centre for 3D Printing and Stratasys jointly developed a 3D-printed drone with embedded electronics. A major challenge was finding electronic components that could survive the high temperature of the printing process, particularly because the drone body was made from high temperature engineering thermoplastic [17]. Although still experimental, electric wires were also embedded in plastic via FDM using a modified nozzle which feed the wire while heating it resulting in a strong bond with the plastic [18]. Another FDM based approach to embed conductors is the use of conductive filaments. However, this approach is limited to small currents, and is not be suitable for our case where relatively high currents are drawn by the drone motors

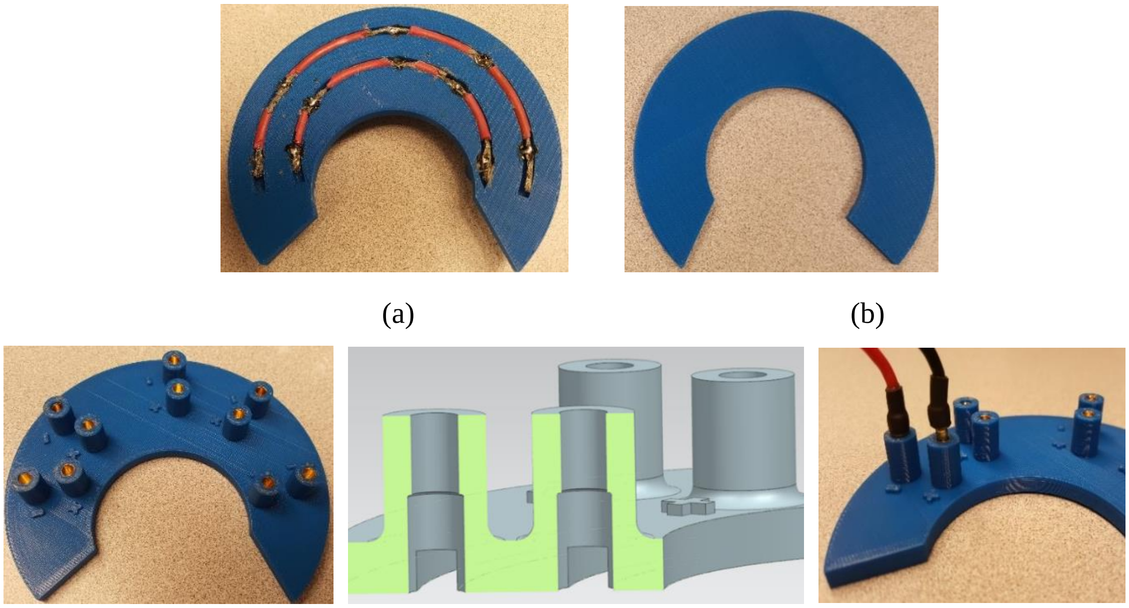
Two approaches were attempted by the students to produce an in-house 3D printed board to replace the commercial board, Figure 6a. The first approach involved creating a cavity with the geometry of the desired conductor, pausing the printing process, placing the conductive artifact and resuming printing. An aluminum plate with rectangular ring shape was chosen to mimic the embedded conductor in the commercial power distribution. Figure 6b shows the plate already placed in the designated cavity as the printer resumed printing to fully embed it while leaving nodes for electric connection, as shown in Figure 6c. Although the process was successful, it proved to be cumbersome as well as involving some risk of damaging the printer nozzle. From a practical point of view, the plate, or any artifact to that matter, might not sit properly in the cavity or might not be perfectly flat which presents the possibility of collision with the nozzle. A manifestation of such issues can be seen in Figure 6b where plastic pile-ups and incomplete deposition can be seen. The conclusion was that this approach, while possible, it is not practical.



(a) (b) (c)

Figure 6: 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

To circumvent the above issue, students developed an alternative approach for embedding electric wiring in 3D-printed power distribution boards. Instead of embedding conductors during the printing process, they redesigned the board into two parts, which, upon assembly, produce the desired cavity where wires need to be embedded. After the two parts are printed, wires can be easily placed in the part with the designated feature followed by the assembly of the second part to create the board. Figure 7 (a) shows the bottom side of the top part of the board which contains the recess where the wire is placed, while Figure 7 (b) shows the lower part, which is simply a cover. Additionally, the flexibility of this approach allowed the insertion of bullet connectors to the top part of the board, Figures 7c and 7d. As explained in Section 3.2, this feature enables easy and fast connection of the motor controllers' wires to the power distribution board, Figure 7e, by eliminating the need for soldering, as in the standard approach, Figure 4.



(a) (b)

(c) (d) (e)

Figure 7: Alternative approach for embedding electric wires in a two-part 3D printed distribution board, (a) bottom side of the top part showing wires placed in designated channel, (b) bottom part, (c) top side of the top part with bullet connector at nodes (d) internal details of top part, and (e) demonstration of connecting at a node

3.4 Detachable compact propeller guard

To protect propellers from damage due to accidental collisions, propeller guards are usually installed on drone arms, particularly if the drone is in its testing stage, as in our case. Although guards can also provide the aerodynamic benefit of increasing thrust, this aspect is not considered here. To this end, students decided to design a detachable guard which can be installed if needed or removed to reduce the overall weight of the drone. Figure 8 shows the first attempt at the guard design, which consisted of a single-piece that assembles to the arm using three pins. As a single piece, however, the guard was not printable because its size exceeded the print volume dimensions, a common limitation of 3D printers

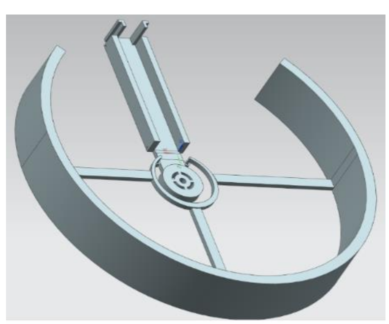
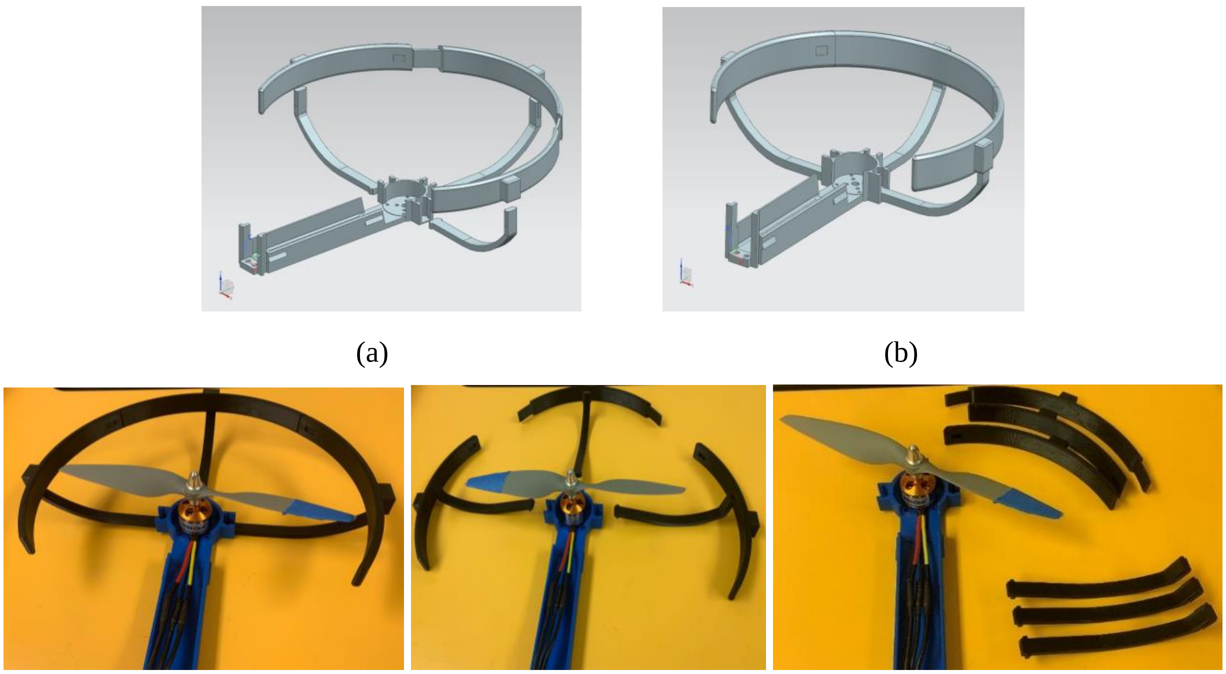


Figure 8: First iteration design of a one-part detachable propeller guard with a diameter of 15 in

To overcome this obstacle, the guard was redesigned into multiple parts which assemble quickly without the need of tools. If not needed the parts can be easily disassembled and compactly packed to minimize storage requirements. Figure 9 a and b show the CAD model, exploded and assembled, respectively, of the redesigned guard consisting of three radial connecting arms and three peripheral sections. The radial arms connect to the peripheral sections and to the end of the drone arm through locational fits with small interference to secure them in place. The peripheral sections mate with each other as shown. Figure 9 c-e shows the actual parts built via FDM, how they assemble and how they pack compactly if the guard does not need to be installed for the particular mission, respectively.



(a) (b)

(c) (d) (e)

Figure 9: (a) exploded and (b) assembled CAD model for the propeller guard, respectively, (c) assembled and (d) disassembled 3D printed, respectively, and (e) illustration of the compact packing of the guard

Throughout the process of developing the solutions described above, students gained valuable experience in AM manufacturing and what designing for AM implies. The following is a broad categorization of those experiences:

- Benefits of AM:
  - Students experienced first-hand how AM empowered them to innovate through the iterative process of design, quickly build functional prototype, and test it, resulting in significantly reduced product development cycle.
  - They also realized that the ease of creating complex geometries by AM allows them to conceptualize without constraints.

    - Manufacturing aids: in two instances during their work, students realized that they can capitalize on the benefits of AM to build manufacturing aids including a fixture to facilitate soldering and another for assembly of the power distribution board

- Limitations of AM:
    - Students learned first-hand that FDM printed parts are weaker in the build direction than in the build plane and that this anisotropy poses certain constraints on the design. Snap fits is one example which demonstrates that a cantilever feature whose axis is normal to the interlayer interfaces is more susceptible to fracture than that whose axis is within the layer.
    - Another limitation of AM is the accuracy and repeatability of the dimensional and geometrical tolerances of features. Identical features in CAD built at different locations within the same print job had different fit relationships. Additionally, the resolution of the printer in the build (z-) direction can result in form and fit functional discrepancy from the CAD model
    - Students realized that, in general, AM printers have limitations on the maximum part size which can be built.

Apart from the technical skills, we also believe that students have gained, or at least got exposed to, valuable skills such as multidisciplinary team work, product development, and entrepreneurship while becoming better prepared for the engineering workforce. In the following section, the students' gains in these areas are evaluated by an independent external evaluator.

4. Student learning outcomes

As part of the overall project evaluation, a structured focus group was conducted by an independent external evaluator to examine students' learning outcomes and experiences. While the sample included all participants, it was too small (n=6) for meaningful statistical analysis. Therefore, the focus group was used to gather feedback and descriptive data from all participants to be used to inform the program leaders and develop additional data collection tools for improved assessment. All six students were African American, majoring in Aerospace, Mechanical, and Electrical and Computer engineering disciplines with project experience ranging from one semester to four semesters. This focus group was guided by three primary questions:

- What aspects of this experience are especially valuable?
- In what specific ways have you benefitted from your experiences? and
- What aspects of the mentoring and advisement process have gone especially well and what advice do you have to better serve students?

The focus group was conducted virtually (via Zoom) and recorded so the independent evaluator could review the audio transcript when coding the data for primary themes in response to the questions above. An a-priori coding system was used when examining focus group responses, especially in relation to guiding question 2 above. That is, the focus was on specific ways in which benefitted in terms of:

- understanding of additive manufacturing and the role it plays in product development (especially in the aerospace industry),
- ability to work in interdisciplinary teams,
- Entrepreneurship skills and product development skills,
- academic knowledge, and
- preparation for jobs and careers

Findings - Overall, students indicated that their experiences in this project have been very beneficial. Students highlighted the opportunities they had to work with students from other disciplines and apply theory they learned in classes and apply it to projects related to industry and additive manufacturing. Students highlighted the interdisciplinary nature of the work and how they benefit from learn from each other's perspectives and areas of expertise while developing their teamwork skills. They also described the improvement of their communication skills as they had to learn to communicate effectively, avoiding technical jargon as they interact with others outside their immediate area of expertise. Finally, students described the one-on-one consultation time with a faculty expert as valuable and requested this as often as possible for all students. The primary themes and illustrative quotations are summarized in the following table.

Theme and Examples
Understanding of additive manufacturing and the role it plays in product development -This experience helped show students how important manufacturing as a whole is important in product development, describing this experience as an opportunity to apply the theory learned in classes and preparing them for internships and careers. One student stated "When you design a product, it is important to know how the part is assembled to better understand how each piece interacts with each other. This is especially true in the aerospace industry because it allows for rapid prototyping at a relatively low cost compared to other production methods." Another student described these experiences related to additive manufacturing as critical in securing an internship.
Ability to work on interdisciplinary teams -All students agreed that the interdisciplinary nature of the project helped them gain academic knowledge, teamwork and collaboration skills and communication skills. One student specifically indicated "In this lab, we have to rely on each other for things including information on drone data, soldering or designing help, or even just to bounce ideas off of each other." Another stated "I had the opportunity to work with people of different backgrounds to achieve a common goal."
Entrepreneurship skills and product development skills – -Three students specifically offered comments in relation to entrepreneurship and product development, describing how their work impacted and depended on others. "We each helped

each other get a better understanding of the product we were developing and understood how it all came together." –"I had the chance to work on product development with many other students and learned how to look at a product in its entirety. I also learned how to ask questions outside of my area of manufacturing. How will this be built? What will power the product? What if a part breaks? How likely is it to break?"
Increase academic knowledge -All students agreed that their experiences helped them apply knowledge they gained in coursework and think differently about the content so they could explain it to someone outside their immediate area of expertise. The knowledge gained in coursework is more focused on theory while what they were gaining in this project was the ability to apply their knowledge to real world situations, affording them opportunities to apply the engineering principles addressed in classes and realize the practical applications of what they had been learning in their degree programs. One student also described learning how to more effectively communicate his content knowledge to other students who are in other disciplines.
Preparation for jobs and careers - While all students agreed that this experience is preparing them for jobs and three made specific comments. Students emphasized the interdisciplinary nature of the work and the role of additive manufacturing in product development as most helpful in preparing for jobs and careers. One student described the opportunities he/she had to apply these experiences during an internship that led to a job opportunity. Another student described gaining "time management and organizational skills" that would be essential for a job or career while another student indicated that this experience has "opened my eyes to the potential of research, and was a major reason I decided to go to graduate school."
Benefits of advisement and mentoring -Students valued this experience as an opportunity to make mistakes and learn from those mistakes. One student specifically described the benefits of having a technical mentor and a practical mentor/project manager, affording him opportunities to gain technical knowledge and skill as well as how to work with others. Another student emphasized the value of his mentor having him keep a journal and prepare a manual detailing what he was doing so other students can learn from his experiences. Two other students commented on the value of having one-on-one meetings with a faculty expert to get feedback on their work and learn ways to improve all students should get one-on-one time with faculty every 2 weeks.

5. Conclusion and Future work

To support workforce development for the current needs of the aerospace industry, and industry in general, a multidisciplinary team of engineering students were tasked with the full development of a modular quadcopter drone, including structural/aerodynamical design, electrical/electronic system integration and manufacturing. AM was the driver for both design and manufacturing, which, based on our experience, proved effective in facilitating students' innovation and maximized their learning outcomes. Our mentoring approach also seemed to have produced the desired outcomes. Students' innovations included detachable drone arm which integrates structural and electrical assembly in one step, detachable propeller guard which can be disassembled and compactly packed, and a concept for 3D printed tailorable power distribution board. Through a focus group with the participating students, an external independent evaluator found that students not only gained technical insight but also interdisciplinary team work skills, entrepreneurship exposure and overall improved career preparedness. Besides continued enhancement of modularity and multi-functionality of the drone, future work will focus on testing of the already developed designs, as is the case of real-life product development. In the case of drones, that might include airworthiness test per FAA regulations.

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