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Capstone Project: Development of FDM 3D Printer Tool for Industrial Robot

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This paper (poster) presents the organization of the course, as well as the goals and outcomes of the project as they relate to the course and program objectives. The paper also provides a detailed overview of the first-phase prototypes designed by undergraduate students in an engineering technology (ET) capstone course. Opportunities for future development and next steps are also discussed.

Introduction

While additive manufacturing, such as polymer 3D printing, has seen a recent surge in popularity in industrial robotics [1-3], there is a considerable gap in the literature for practitioners who wish to implement these technologies in their teaching and learning. Furthermore, the extant literature often fails to convey the plans and details necessary to replicate or expand upon studies in this line of research, as detailed descriptions of the FDM tooling solutions used in various experiments are not often clearly described in an easily reproducible way. This paper (poster) presents the results of an engineering technology student capstone project that sought to develop a low-cost, flexible, and modular end-of-arm 3D printing tool that can ultimately be used to demonstrate fused deposition modeling (FDM) concepts using an industrial robot. To achieve this goal, students considered which, if any, widely available desktop FDM components could be adapted to solve the problem. After meeting with stakeholders, students followed a constraint-based, research-oriented approach to designing and developing a prototype product to enhance future learning opportunities at Illinois State University.

Background

3D Printing with Industrial Robots

3D printing is being revolutionized by industrial robots, which allow for the creation of larger and more complex objects with increased speed and precision. By integrating robotic arms with 3D printing technology, manufacturers can automate the additive manufacturing process, improving efficiency while significantly reducing the time and cost of producing large-scale parts compared to traditional methods. Using robots in 3D printing enables the fabrication of complex geometries and incorporates features that would be challenging to achieve with conventional 3D printing techniques [4]. Several companies, such as KUKA and ABB, offer robotic arms specifically designed for 3D printing applications, further highlighting the growing importance of this technology in various industries. This approach also allows for greater flexibility in design and the use of a broader range of materials, including metals, as demonstrated in applications like wire arc additive manufacturing (WAAM) [5] and concrete, expanding possibilities for large-scale construction [6].

Capstone Course Organization

The ET capstone course is a culminating experience based on a combination of their previous coursework and exploration of a hands-on project related to their future professional pathways. The course is designed to engage students in studying industrial production systems, including product, manufacturing, and plant engineering, through managing a production project. To achieve this goal, students were divided into teams with members with various technical competencies to develop and implement a lean production process. The activities of this course are expected to assist the student in transitioning from the classroom to positions of responsibility within a corporate setting. To this end, there are several course goals, objectives, and student outcomes. The course objectives are as follows:

Upon successful completion of this course, students will be able to:

1. Apply the four fundamentals of management to a production situation: planning, organizing, leading, and controlling.
2. Analyze a specific project to identify the separate steps, associated costs, and resources needed for completion.
3. Develop a schedule and budget for an assigned project.
4. Apply and exhibit an understanding of product design, process planning, production planning and control, quality control, jig and fixture design, prototyping, and project management with regard to an assigned project.
5. Synthesize the interrelationship of various manufacturing documentation.
6. Control both finances and quality in a simulated manufacturing environment.
7. Utilize project management software to help plan, schedule, and budget a project.

Additionally, five ABET student outcomes (SO) are addressed in this course:

- SO 1: an ability to apply knowledge, techniques, skills, and modern tools of mathematics, science, engineering, and technology to solve broadly defined engineering problems appropriate to the discipline;
- SO 2: an ability to design systems, components, or processes meeting specified needs for broadly defined engineering problems appropriate to the discipline;
- SO 3: an ability to apply written, oral, and graphical communication in broadly defined technical and non-technical environments; and an ability to identify and use appropriate technical literature;
- SO 4: an ability to conduct standard tests, measurements, and experiments and to analyze and interpret the results to improve processes and
- SO 5:an ability to function effectively as a member as well as a leader on technical teams.

Typically, capstone students are given a general outline of the project requirements and a timeline. They are then responsible for refining the problem statement about the specific design problem and customer scope while considering the constraints of the learning and lab spaces, time, resources, etc. Then, they create their own proposed project schedules and deliverables before embarking on the detailed work of the project. Examples of these details are presented in the following sections.

Project Overview

During the Fall 2024 semester, fourteen students were in the course, which was divided into three project teams. Two teams had five students each, and one team had four students. Each team consisted of student “experts” who maintained responsibility for key roles in the project (e.g., CAD Designer, Project Manager, CNC Lead, etc.). However, teams worked cooperatively throughout the project to produce and present a final project by the end of one semester (16-week course). During the semester, there were several milestone “checkpoints” with the course's instructor and the project stakeholders. The project was designed with a "customer" in mind so that students could follow the design process and manage a project in a real-world way. The project began with a client statement as follows:

> Over the past few years, additive manufacturing (particularly 3d printing or "3DP") has become feasible and desirable using industrial robots. You can find many examples from manufacturing, construction, and creative fields. Often, these artifacts explore novel methods of additive manufacturing (such as non-planar fused deposition modeling – FDM, for example) or the use of materials like concrete instead of plastic filament, etc. Despite the underlying technology being similar to desktop FDM 3DP processes, the current levels of complexity, inflexibility, and lack of modularity (systems are usually either proprietary and/or are too specifically designed to be able to work with a variety of robots or for various applications), and high costs associated with robotic 3DP systems present a significant limitation for those interested in learning, research, and innovation.
>
> Since this is a rapidly emerging technology with great potential for current and future real-world applications, coupled with a substantial gap in available resources for learning and research, I am inviting you to participate in the design and development of a functional product/ system that addresses these issues.
>
> It is expected that your team will further refine the problem to understand the criteria and constraints that will lead to the design and build of a functional prototype. Then, you will test your development using an industrial robot system and present your results/ findings to a community of stakeholders.

Immediately following the presentation of the client's needs, students were responsible for developing a written project plan that included the following before beginning their project work:

- An overview of the project in their own words
- A statement of the purpose of the project
- A description of the benefits and all stakeholders and project participants
- Project management considerations such as:
    - Team members and key skills/experience
    - Project tasks (work breakdown structure)
    - Gantt Chart
    - Linear Responsibility Chart
    - Budget
    - Project Tracking
- A percentage Completion Matrix to show the percentage of the work completed at each reporting period as compared to your initial plan
- An explanation of contingency plans the team has in the event of any unexpected difficulties or delays

Once the project proposal was completed, students began to work through their plans. The following section will discuss the results of the projects, including aspects of design, planning, organization, and project management from each of the three teams.

Project Implementation and Results

This section presents the results of the project implementation methods, organized by team, in order of the course timeline. One of the first project artifacts was the creation of team planning documents. These included items such as a Gantt Chart, as shown in Figure 1.

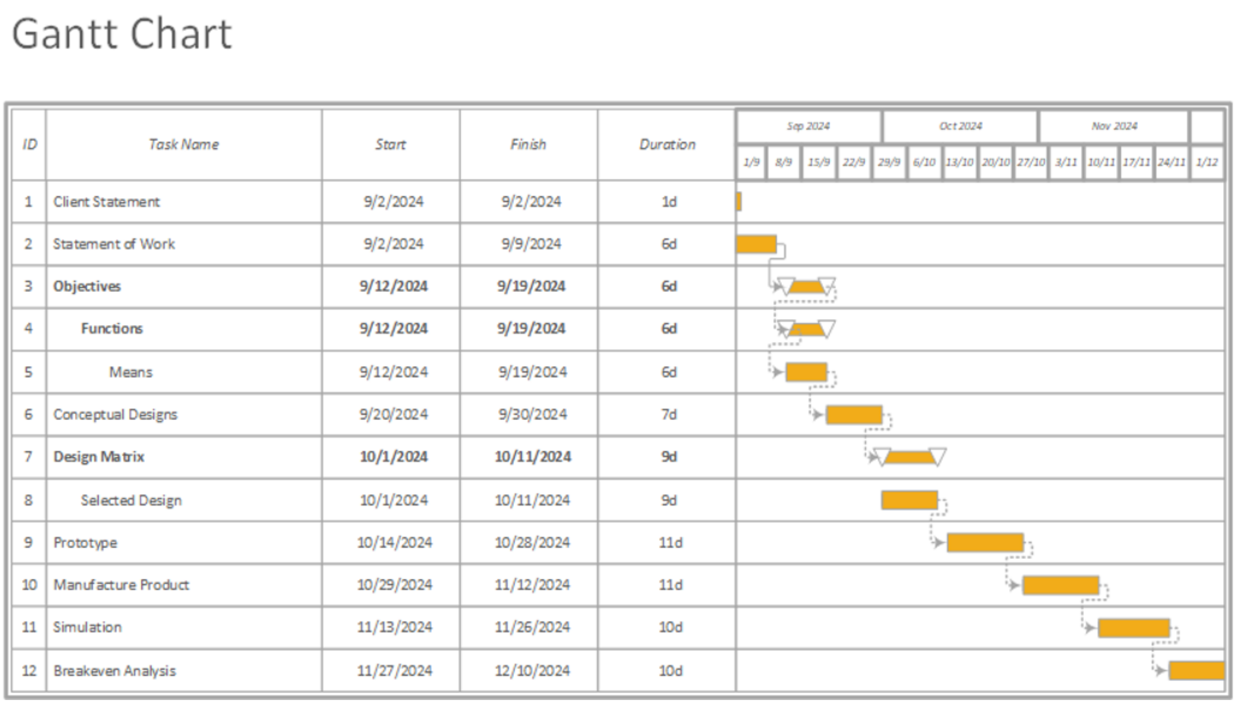

Figure 1. Example: Student-created Gantt Chart for Project Planning

The next phase was to develop conceptual designs. The goal of the conceptual design phase was to create a simple visualization of the product that highlighted the design's key functions, requirements, and constraints before proceeding to CAD work. This was done through sketching with annotations. Figures 2, 3, and 4 present an example from each team.

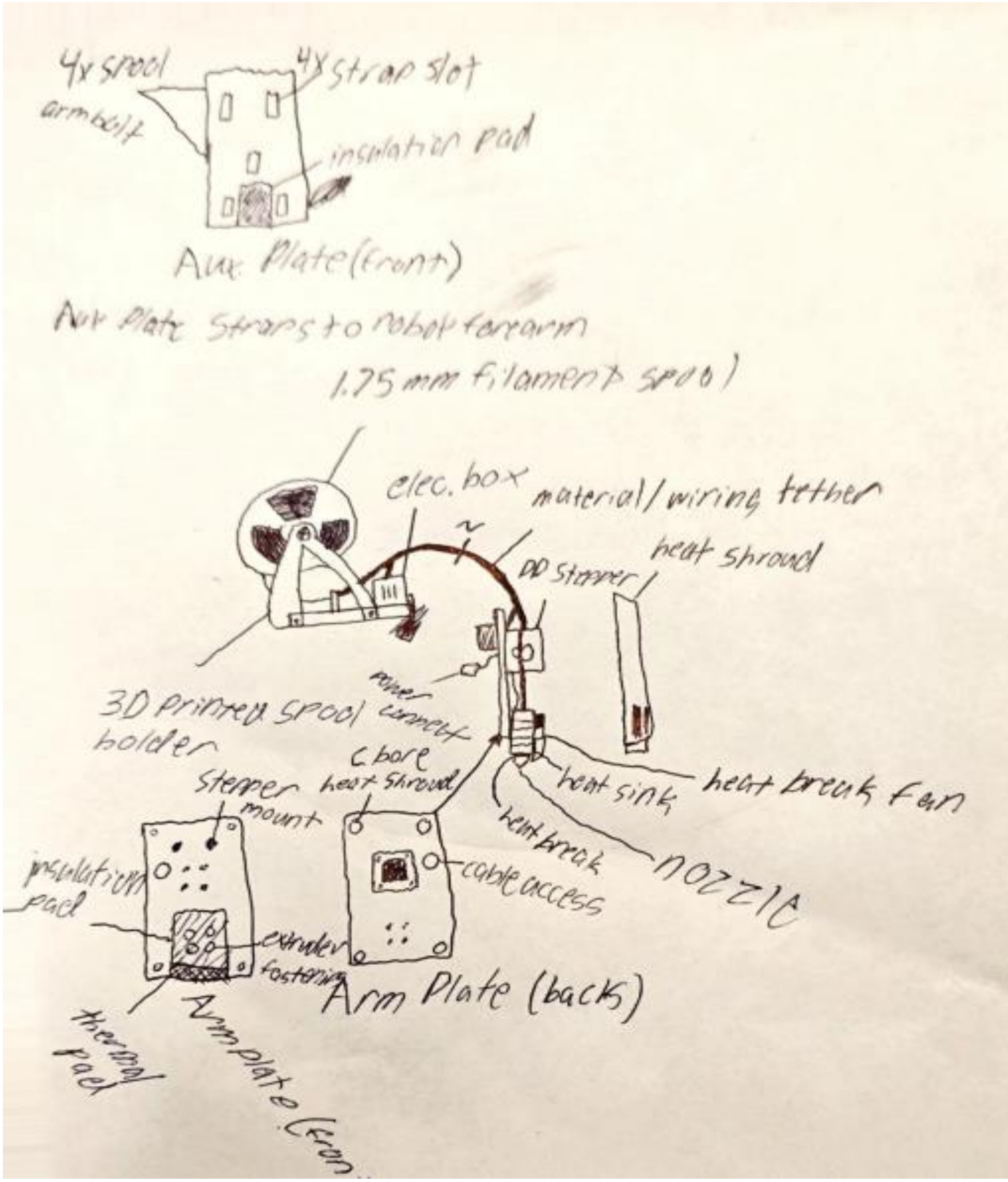

Figure 2. Team 1 Concept Drawing

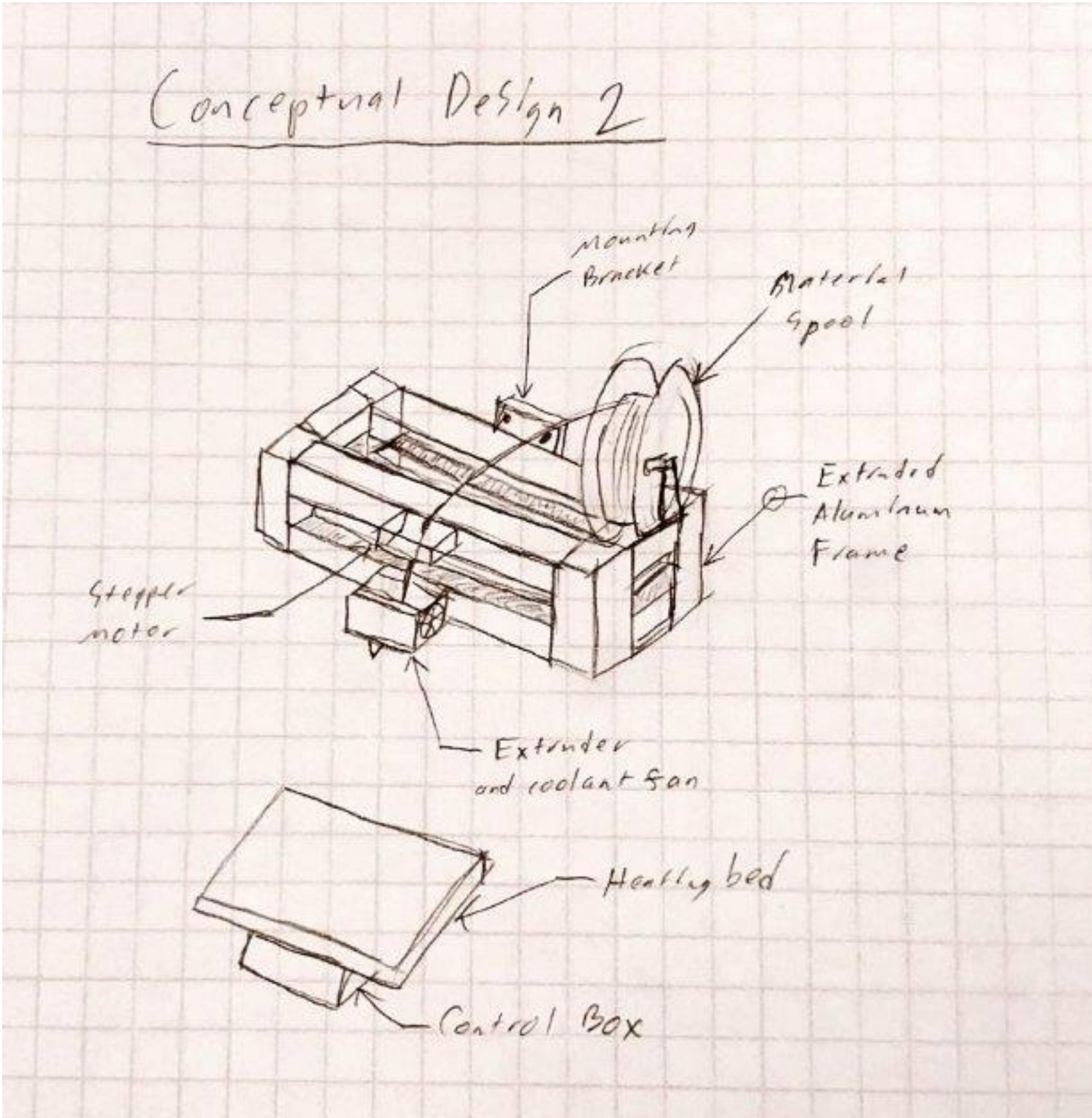

Figure 3. Team 2 Concept Drawing

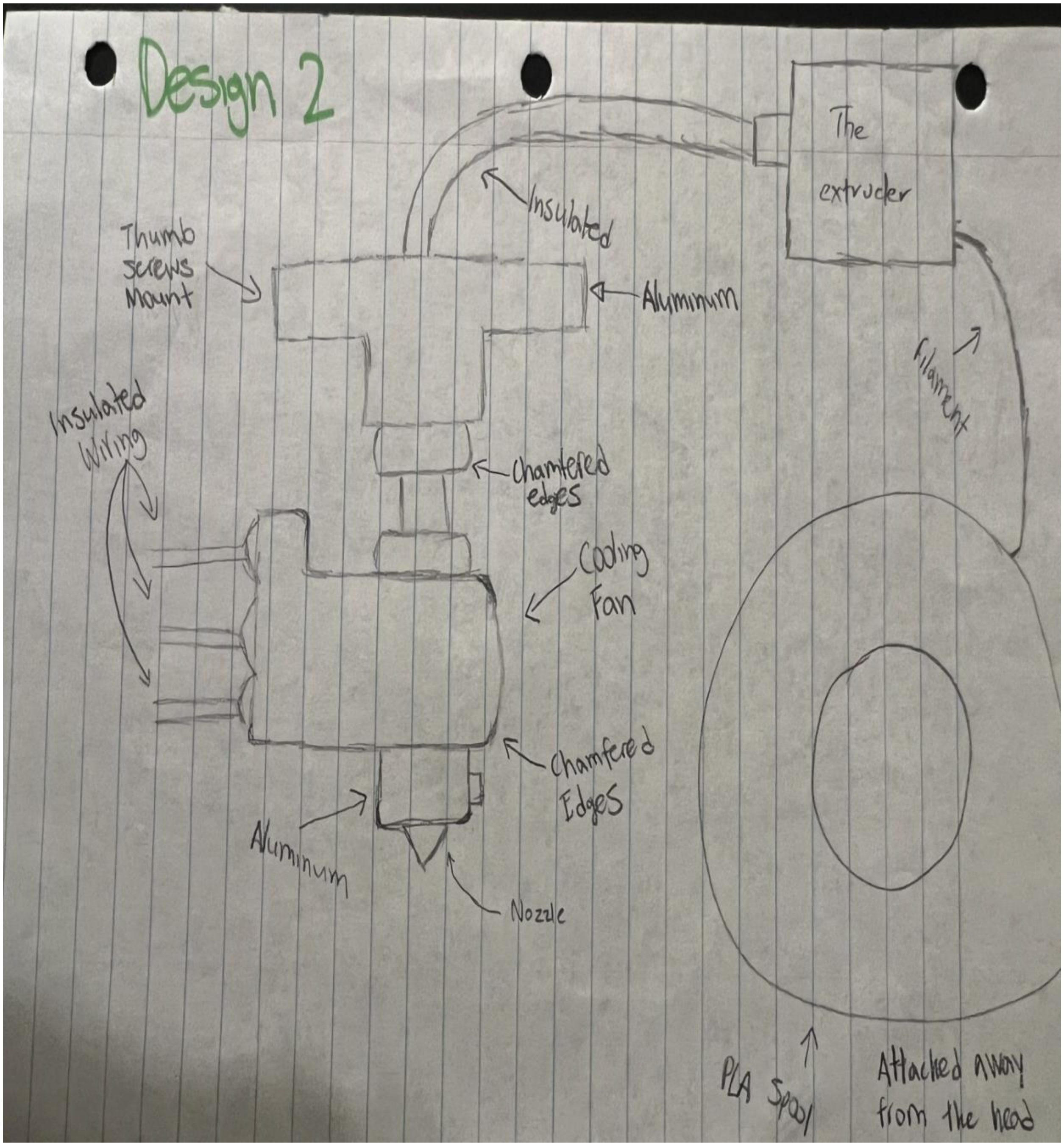

Figure 4. Team 3 Concept Drawing

Next, each team developed a decision-making matrix to determine which design (or which combinations of design elements) would be considered for the next step: the development of CAD models of the product. Then, to facilitate fabrication, machining, and other production techniques of the project, working drawings and plans were developed from the CAD models, and manufacturing plans were produced. Figures 5, 6, and 7 present each team's CAD model(s) and their produced prototype.

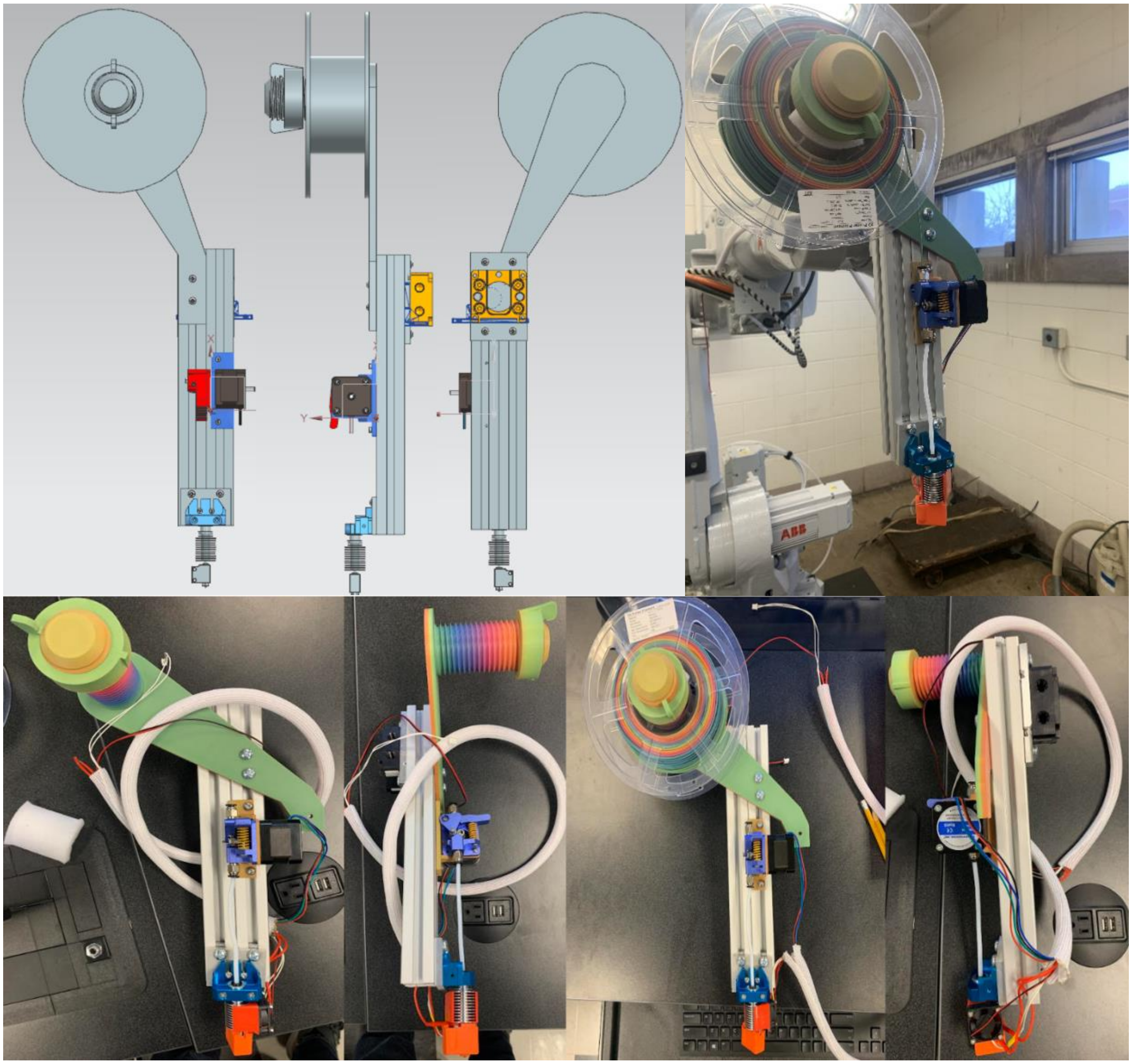

Figure 5. Team 1 CAD and Prototype

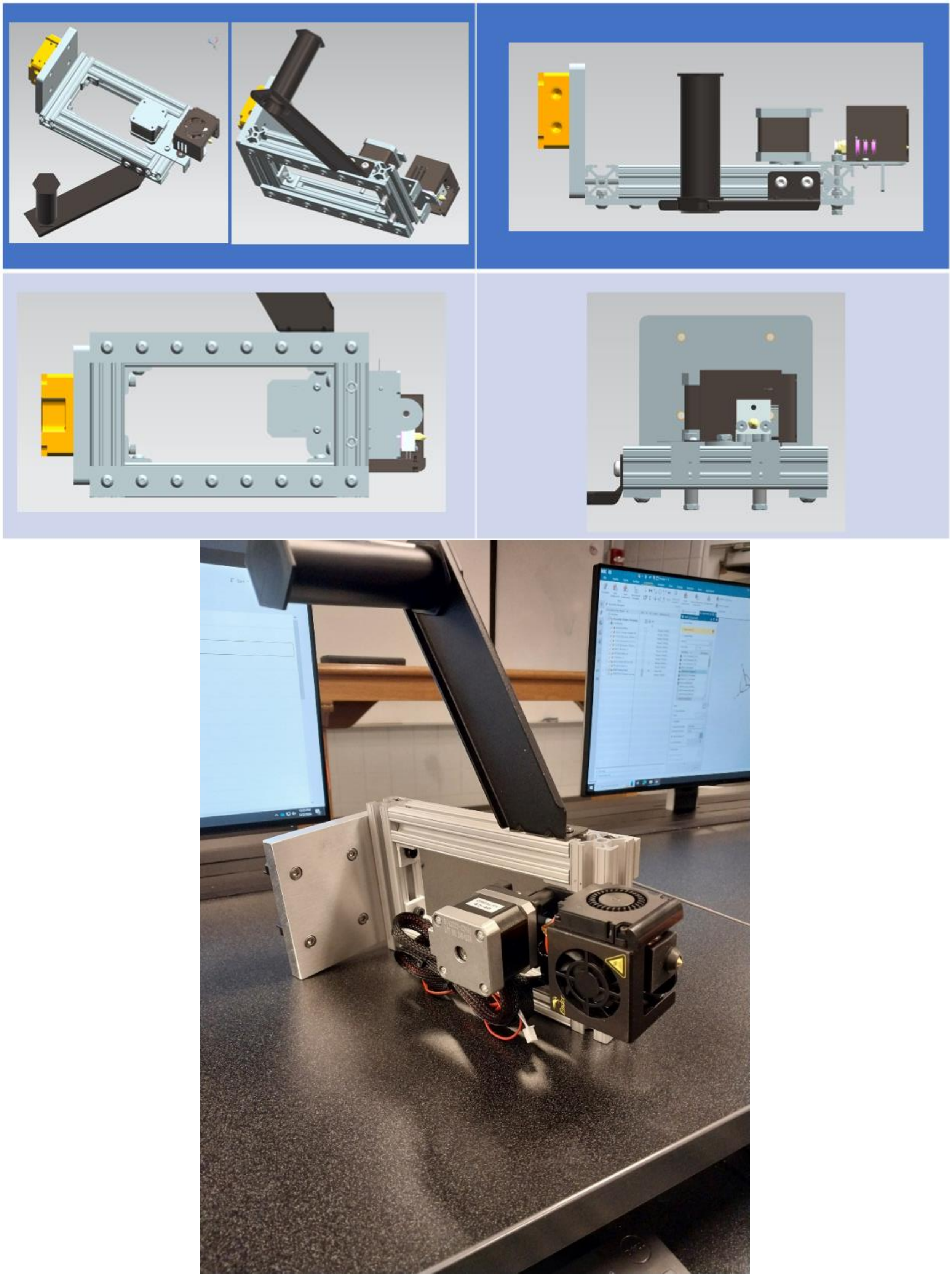

Figure 6. Team 2 CAD and Prototype

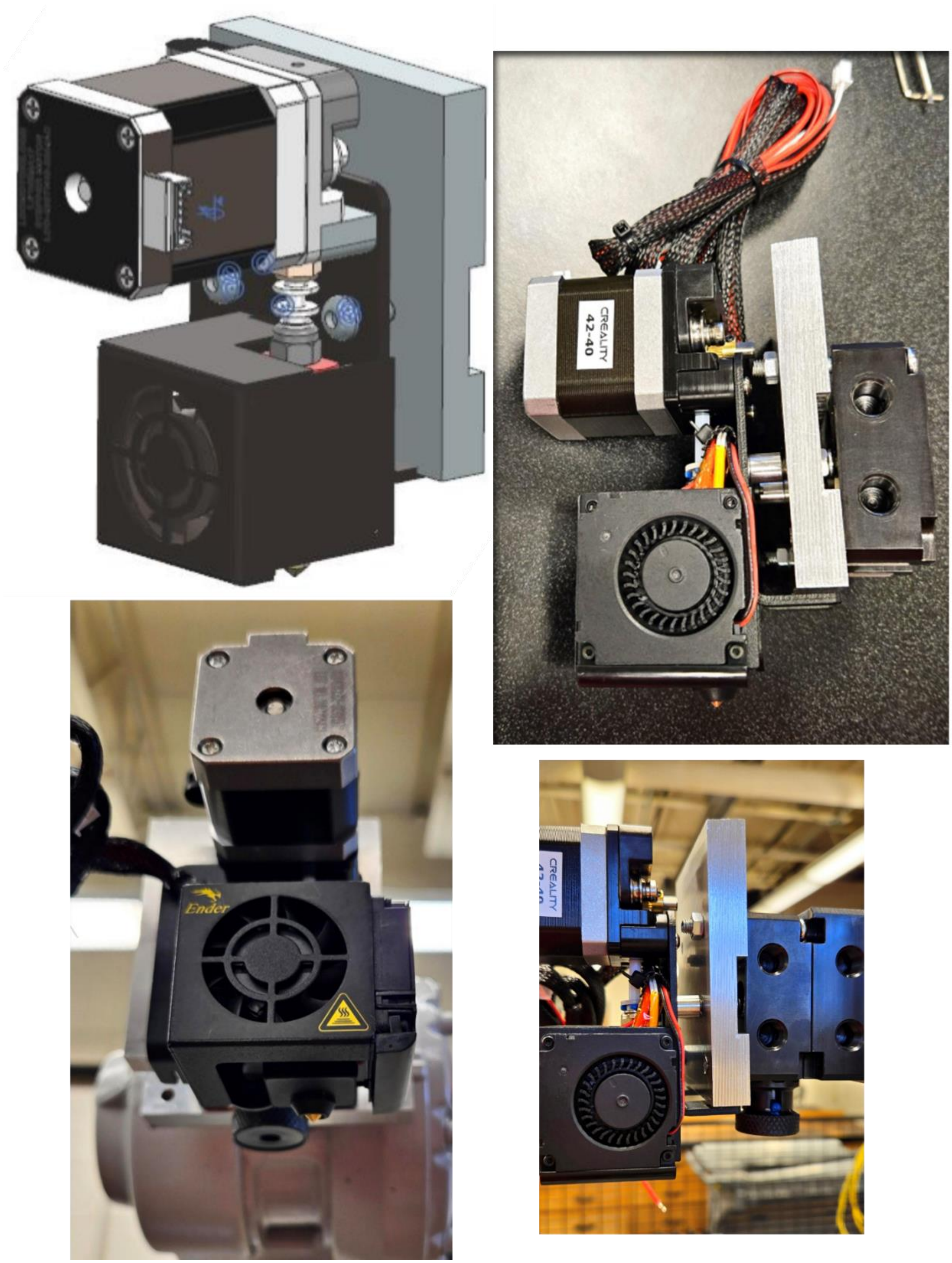

Figure 7. Team 3 CAD and Prototype

A bill of materials was produced for each product. Each team was able to develop a prototype for around USD 200. Table 1 outlines a simplified bill of materials needed to make each industrial robot 3D printing tool by team.

Table 1. Bill of Materials by Team

Team 1		**Team 2**		**Team 3**	
Part Name	**Cost**	**Part Name**	**Cost**	**Part Name**	**Cost**
Direct Drive	$12.99	Aluminum Extrusion	$6.06	Extruder	$15.99
Machine Screws	$22.49	L-Brackets	$28.68	Hot Plate	$39.99
Hot End	$32.38	M5x40 Bolts	$7.78	Stepper Motor	$51.96
End Mount	$10.61	M5x20 Bolts	$17.10	Cooling Fan for Extruder	$8.99
T-Slot nuts	$25.00	M5 lock nuts	$6.14	Hot End with Cooling Fan	$22.99
Cable shroud	$7.64	2020 Endcaps	$8.72	Spool Holder	$11.97
PTFE tube	$8.22	Integrated Extruder Module	$29.99	Aluminum Rods	$17.99
Aluminum Extrusion	$16.26	Spool Bracket	$12.99	Screws	$9.99
Stepper Motor	$12.50	Aluminum Plate	$22.99	Stepper Motor Plate	$7.59
Aluminum Plate	$13.59	Brackets	$49.80	Aluminum Plate	$16.99
Total	**$161.68**		**$190.25**		**$204.45**

After prototypes were produced, an economic analysis was performed to determine the scalability of production and to consider what logistical challenges would be present should the prototype move into a production phase based on the actual manufacturing and assembly processes. At the conclusion of the project term, students presented their results to faculty and other project stakeholders. Each team of undergraduate students provided a conclusion to their projects that included a summary of the project and deliverables and considered opportunities for future development. All three teams successfully created 3D printing tools for robotic arms with different focuses. Team 1 prioritized creating an open-source, affordable tool for educators. Team 2 focused on a low-cost, customizable module. Team 3 emphasized a versatile, safe design that is easily adaptable to different lab setups. In many cases, the students also discussed lessons learned and self-reflected on their development in their oral presentations. The following section will discuss limitations and opportunities for next steps from the faculty instructor's perspective.

Limitations and Next Steps

Future work should consider further refinement and revision of these prototypes. This can be done in a variety of ways. First, notably absent from this work, is the actual testing of the product beyond fitment and basic movements with the industrial robot. This is mainly due to time constraints in the project term. However, this could be enhanced through virtual testing and/or other means of digital twinning. The author of this study has found this to be an effective and engaging way to achieve similar goals in prior work [7], and RobotStudio (the software used to control ABB robots – those for which this tool was designed) can visually and systematically emulate 3d printing process, which would be suitable for further testing and validation.

Second, this work would benefit from physical 3DP control systems development, such as a module that connects the 3DP tool to the control system of the industrial robot. This is not necessarily a difficult task, as several prior works have successfully achieved this and provided adequate documentation for replication [8-10].

Finally, it is clear from this project's final products and artifacts that there are opportunities to improve the application of CAD, project planning, and manufacturability techniques in and around the course. Future iterations of this project should address issues in quality control and management, as well as the iterative design process. Overall, students reported that this capstone project provided a valuable and authentic experience supported by positive responses to peer and course evaluation instruments.

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