International Journal of Engineering Education Vol. 40, No. 6, pp. 1313–1322, 2024
Printed in Great Britain

0949-149X/91 $3.00+0.00

Use of Different Prototype Modalities for Design Communication in Industry-Sponsored, Interdisciplinary Capstone Design Teams during COVID-19*

PABLO LUNA FALCON
Department of Aerospace and Mechanical Engineering, University of Arizona, USA. E-mail: pluna1@arizona.edu

HANNAH BUDINOFF
Department of Systems and Industrial Engineering, University of Arizona, USA. E-mail: hdb@arizona.edu

JULIA KRAMER
Department of Mechanical Engineering, University of Michigan, USA. E-mail: kramerju@umich.edu

JANNATUL BUSHRA
Department of Systems and Industrial Engineering, University of Arizona, USA. E-mail: hdb@arizona.edu

Students' participation in a culminating engineering design experience is an important element of many undergraduate engineering programs. A typical outcome of this experience is for students to communicate a clear understanding of the design problem and associated constraints, describe their design process, and illustrate that their final design meets its requirements. Effective communication skills are an influential factor for success and are considered a critical learning objective for capstone engineering courses. Even though visual media such as sketches and prototypes are an essential means of communication, little work has been done analyzing their use in students' design communication. In this study, we seek to identify and compare prototype usage of different modalities among student design teams. Data was collected from approximately 8-minute video presentations that served as a final deliverable in an interdisciplinary capstone course during the 2019–2020 academic year, which was interrupted by the COVID-19 pandemic. Prototypes shown in the videos were classified by prototype category and the duration of prototypes presented in each video was recorded. We sought to understand how prototype usage varied between teams who were given awards from panels of judges and to identify patterns in prototyping among teams with different compositions of student majors. The results indicated that a larger proportion of prototypes were displayed by awarded teams compared to teams who did not win an award. Several differences in digital and physical prototype usage were seen among engineering disciplines. Across all teams, a higher use of digital prototypes was identified when compared to physical prototypes. Mechanical teams showed the highest proportion of physical prototypes, while interdisciplinary and chemical engineering teams showed the least. This study contributes to the understanding of visual artifacts and prototypes as means of communication (especially virtual communication) and provides guidance for student designers for effective demonstration of engineering projects.

Keywords: prototyping; capstone design; virtual prototyping

1. Introduction

In industry-sponsored design projects, students must work to complete the engineering design process to achieve an outcome that satisfies the sponsor, often with only infrequent communication from the sponsor representative. Students must effectively communicate their understanding of the design problem, progress through their design process, and demonstrate the effectiveness of their final design outcome to the sponsor. Communication skills are viewed as critical learning objectives of capstone courses and as such, are frequently assessed by capstone faculty to evaluate student performance [1–4]. Effective communication among team members can lead to a shared understanding of the design and better long term performance [5–7]. External communication may be especially important in interdisciplinary capstone design teams, where industry sponsors may have little awareness of students' varying background and competency [8]. While prior research in capstone design projects has primarily focused on written and oral communication (e.g., [9–11]), the use of physical or visual media such as prototypes is another important means of communication. There is a need to raise awareness of prototypes' role in communication to enable designers to utilize prototypes for communication more effectively [12].

Prior work has shown that prototypes enable richer communication between designers and with external stakeholders, catalyze learning, and serve as milestones during development [13], all which could lead to greater performance and better quality of design outcomes. One study showed that late adoption of physical prototypes during a design

* Accepted 10 September 2024.

process was a characteristic of low-performing industry-sponsored project teams [14]. Different prototype modalities (e.g., physical or virtual/digital) have different strengths and weaknesses depending on what point in the design process they are being used and the purpose of the prototyping use. Novices, including student designers, are more aware of their use of prototypes for *testing and validating* design concepts, and are less aware or intentional in their use of prototypes to *communicate.* Perhaps as a result, there are still open research questions as to how novice designers use prototypes for communication [15, 16].

Another element that may affect prototype usage is that there is a trend towards increasingly remote collaboration and use of model-based design, indicating a growing interest in virtual or digital prototypes [17]. The COVID-19 pandemic dramatically impacted engineering education programs across the world, forcing many instructors to switch immediately to remote learning, which can be challenging for lab-based and hands-on courses like capstone design [18, 19]. The pandemic disruptions present an interesting opportunity to observe how remote learning may have impacted students' prototyping usage and forced more students to utilize virtual prototyping.

In this study we seek to understand how prototypes of different modalities are used by awarded student design teams, and compare this usage to non-awarded teams, where awards were given by a panel of industry sponsor judges. Our aim is to contribute to the literature that explores the role of prototyping on project success; while we are not explicitly comparing measures of success in this paper due to a lack of available data, we leverage awards as a metric that relates to but does not necessarily equate to success. Our data set is drawn from projects conducted over the 2019–2020 academic school year, presenting an opportunity to observe students' prototyping patterns when some of their design work was conducted remotely. Our research questions are as follows: (*RQ1)* To what extent does frequency of use of prototypes for communication vary between awardees and non-awardees? (*RQ2*) To what extent do awardees use virtual versus physical prototypes for communication, and how does this compare to non-awardees? (*RQ3)*: Are patterns in prototyping usage for communication different among different engineering disciplines?

This study contributes to our understanding of the relative benefits of virtual and physical prototyping for communication purposes. We also leverage our rich, observational dataset to illustrate common prototyping practices of engineering students for communication external to their design teams and how this varies across majors.

2. Methodology and Results

The data for our analysis is drawn from videos of capstone student design teams presenting to stakeholders, peers, and industry sponsor judges at a large, public R1 university. In these presentations, students summarize their project and its outcomes by describing their project requirements, their design process, their testing and verification results, and by demonstrating their final prototype. The videos are submitted as part of the final deliverables at the end of a two-semester capstone design course. We excluded three videos which focused on civil engineering projects, four videos describing projects related to mining, and two videos on industrial engineering projects as these were viewed as outliers with little use of prototyping. Our final dataset includes 105 videos representing the same number of teams. The average duration of the videos was 8 minutes and 24 seconds, and video lengths ranged from 6 minutes and 31 seconds to 15 minutes and 50 seconds.

2.1 Coding of Prototypes

From each video, we identified each presentation of a prototype and the time stamp at which it was shown in the video. The codebook for categorizing prototype categories was developed iteratively by two coders, who watched a subset of the videos and discussed prototype categories. Each prototype was categorized into one of 12 categories (Table 1). While the definition of prototypes varies [20, 21], we purposely employed a broad lens of prototyping and tried to capture all types of artifacts which could be considered a prototype based on the artifact's use for helping the design team communicate some aspect of what they created through their design process. For example, we considered system diagrams a type of prototype because such diagrams often represented how subsystems interact with each other and how users might interact with the design itself. Sketches were also included as a type of prototype. We did not, however, include images of purchased components unintegrated into a larger system as a type of prototype because it was not an approximation of the product being designed. While we could have used a narrower definition of prototyping to scope the coded categories, we felt it was important to be broad given the range of engineering disciplines and types of projects included in our dataset.

Images or videos which were displayed in the presentation for less than 3 seconds were excluded from coding, as were images that were displayed as part of team's posters (many teams included a static image of a three-panel poster, which was a separate required course deliverable, as part of their video).

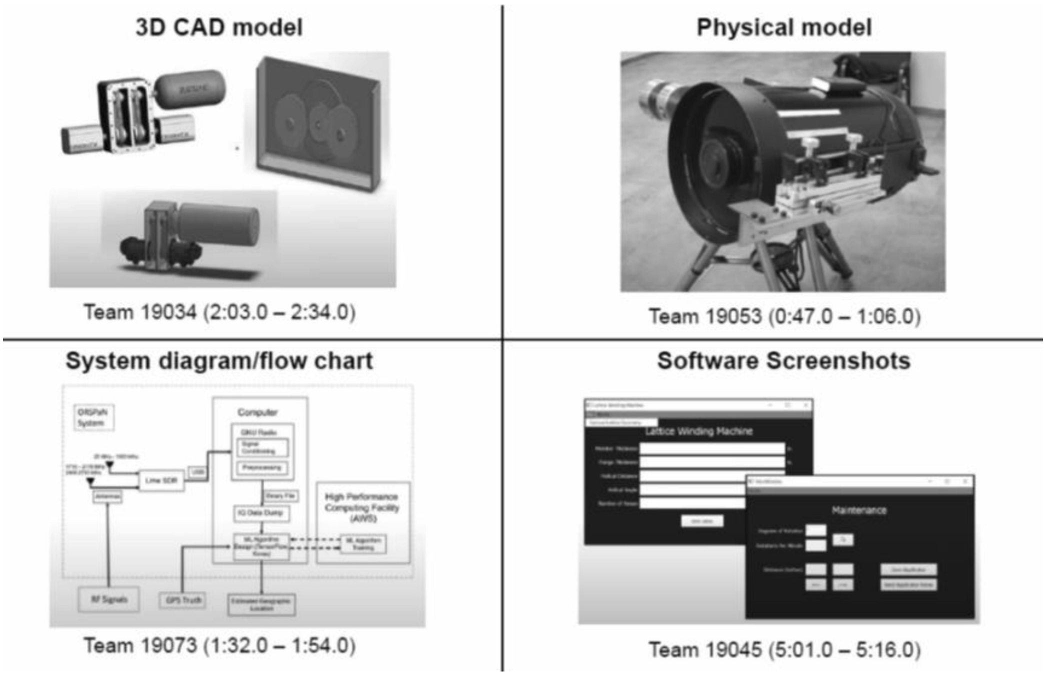

Fig. 1. Examples of prototype coding for several categories.

We did not code prototypes that did not appear to be created by the team in the video (e.g., prototypes created by another team in a prior year that served as a starting point for this team's design). Examples of some of the coded prototypes are shown in Fig. 1.

After we created our list of categories, we differentiated prototype categories by modality: physical or digital/virtual (Table 1). Physical prototypes existed outside of the digital world and included objects that could be handled and manipulated in the real world. Physical sketches, i.e. sketches that appeared to be drawn by hand without the use of a

Table 1. Description of prototype categories used for coding

Category	Description	Prototype modality
3D CAD model	3D model representing one or more mechanical parts, shown in isolation or in an assembly-type drawing	Digital/Virtual
CAD model in simulation	2D or 3D model shown in a simulation package to determine functional performance, e.g., finite element analysis	Digital/Virtual
CAD model demonstration	2D or 3D model shown with animation of its movement or exploded view animation	Digital/Virtual
Electronics CAD model or drawing	A 2D representation of the connections between electronic components	Digital/Virtual
2D engineering drawing	One or more 2D projections of a mechanical part, typically with dimensions (excludes assembly drawings with no dimensions)	Digital/Virtual
Physical model	Static image or video of a static physical representation of one or more parts of design hardware (excludes photos of off-the-shelf components which aren't integrated into the design)	Physical
Physical model demonstration	Video demonstration of a physical representation of one or more parts of design hardware, showing movement/interaction/functionality of the design	Physical
Digital sketch	Rough visual representation of the design created using a computer program	Digital/Virtual
Physical sketch	Hand-drawn visual representation of the design	Physical
System diagram/flow chart	Flow chart representing individual subsystems in the design, with inputs and outputs	Digital/Virtual
Software/application demonstration	Dynamic representation of software, application, or web application workflow, typically shown in real-time, with the only physical components shown being a screen or display	Digital/Virtual
Software screenshots	Images showing a software GUI or code at a single point in time, with the only physical components shown being a screen or display	Digital/Virtual

computer, were also considered physical prototypes because they were created first in the physical world. Physical demos and physical models could include some digital components such as a software running on a computer screen, but also included physical objects. We will refer to the set of prototypes with a digital modality as "virtual prototypes" to be consistent with existing literature.

After the codebook was developed, a set of 45 prototypes from the videos were prepared and discussed among three raters to finalize the codebook and the descriptions of each prototype category. Then, all three raters completed a code application test of 119 prototypes drawn from the dataset of videos, using the eight most commonly used or most important categories (excluding posters, electronics CAD/drawings, and sketches). To calculate agreement between raters, we used Cohen's unweighted kappa. Between Rater 1 and Rater 2, the unweighted observed kappa was 0.88, between Rater 1 and Rater 3 the kappa was 0.84, and between Rater 2 and Rater 3 the kappa was 0.94, all indicating a nearly perfect level of agreement [22].

2.2 Coding of Teams

To evaluate differences in prototyping depending on the student makeup of teams, we decided to categorize teams based on the majors of the students in each team. Our sample included students from 11 engineering majors so we also coded each student's major, which was typically presented at the beginning of each video and documented in a supplementary program publicly available online. Teams were typically composed of 5 or 6 members. Based on the majors of the students in each team, we categorized teams in one of the following categories corresponding to the common majors: biomedical, mechanical, electrical/computer, aerospace, chemical engineering. A team was categorized as one of those categories if more than a third of the members from a particular major and that same major accounted for the highest percentage of team members (e.g., 3 of 6 team members from mechanical engineering with 2 or fewer members from each other major). With these categories, 24 teams were categorized as mechanical, 6 as biomedical, 14 as electrical/computer, 6 as aerospace, 18 as chemical. The remaining 37 teams did not have one dominant major and were categorized as interdisciplinary.

To categorize teams as awardees, which we use as an indicator of successful design outcomes and successful communication, we rely on judging of industry sponsors. In the year when our data was collected, each team was eligible for one or more of 31 awards (Table 2), which were awarded based on ratings from a panel of judges, mostly representatives from industry. Each award had specific criteria, but most awards were given for excellence in design, innovation, and communication about the design. Historically, these awards often go to teams with the most well-developed prototypes who demonstrate effectively that their design outcomes meet the technical requirements of the project. Two raters independently evaluated all awards and identified awards that met the following criteria: were team-based awards; reflected some element of design outcome, presentation quality, or effective storytelling; were broad enough in scope that teams from different disciplines would be eligible for the awards. Two disagreements were discussed and resolved. Examples of excluded awards include "Best Biomedical System Design" and "Award for Unmanned Aircraft." The final list of 24 awards used to categorize teams is shown in Table 2. All teams who won one or more awards were categorized as awardees (n = 21), while the remaining teams (n = 84) were categorized as non-awardees.

2.3 Post-processing and Data Analysis

After all videos were analyzed we calculated the percentage for all prototype categories present in

Table 2. List of awards we used to distinguish between awardees and non-awardees

Award name	Award name (continued)
Award for Design Above and Beyond	Best Simulation and Modeling
Award for Lifelong Innovation	Best System Software Design
Award for Perseverance and Recovery	Best Use of Embedded Intelligence
Award for Sustainable Manufacturing Innovation	Best Use of Prototyping
Best Design Documentation	Best Use of Wireless Technology
Best Design Using a Data Acquisition and Control System	Engineering Ethics
Best Engineering Analysis	Innovation for Energy Production, Supply or Use
Best Implementation of Agile Methodology	Most Innovative Engineering Design
Best Implementation of Analytically Driven Design	Most Outstanding Project
Best Overall Design	Most Robust Systems Engineering
Best Presentation	Practical Solution/Application Award
Best Printed Circuit Design	Voltaire Design Award

Table 3. Results from two-way ANOVA for total prototyping proportion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
(Intercept)	8.558	1	8.558	185.521	0.000
TeamType	0.539	4	0.135	2.923	0.025
Awards	0.189	1	0.189	4.088	0.046
TeamType * Awards	0.156	4	0.039	0.844	0.501
Error	4.105	89	0.046		

each video. We ensured that all collected timestamps were consistently formatted (mm:ss.0) for easier computations. The duration per time stamp was calculated by subtracting the end time with the beginning time. The total duration per category was then computed as the sum of time per time stamp. The percentage of time the videos dedicated to prototypes was found by dividing the sum of the total coded time per category by the total video duration. This percentage could sometimes be larger than 100%, as certain portions of the video could have been double coded with multiple prototype categories displayed in a single time period. Each individual coded prototype duration was included for the total duration calculation to obtain the required 100% for data visualization.

To identify differences in proportions of prototyping between groups and connections with awards, we conducted an analysis of variance in IBM SPSS. We excluded aerospace teams from this analysis because we observed that aerospace teams were awarded several of our excluded discipline-specific awards, and not any other general awards, possibly indicating that the award tendencies of this discipline were distinct from the other teams. Once these six teams were excluded, two ANOVAs were conducted: one using physical prototyping proportion as the dependent variable and one using total prototyping proportion as the dependent variable. We verified the approximate normality of the residuals for the ANOVA using a histogram and Q-Q plot. The residuals were approximately normally distributed, with some skew and kurtosis, but ANOVA is robust to violations of the normality assumption for residuals. We used an alpha level of 0.05.

3. Results

The results below are organized into several subsections, one for each of our research questions. The last subsection addresses emergent findings and insights not directly related to one of the three research questions.

3.1 RQ1: Frequency of Prototyping in Awarded Teams

Prototypes were an important part of most teams' presentations, with awardee teams showing prototypes for nearly half of their presentations. Non-awardee teams displayed prototypes for a smaller

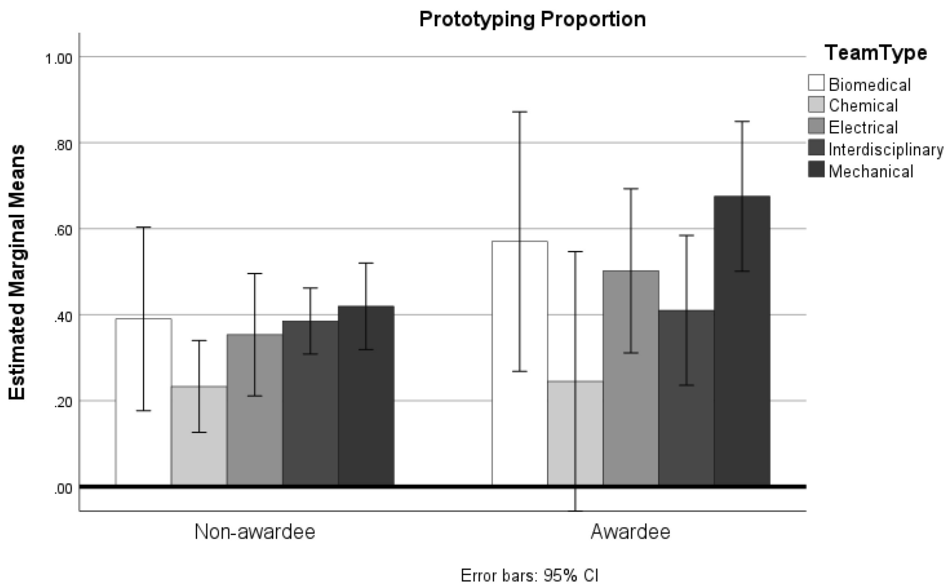

Fig. 2. Comparison of non-awardee and awardee teams of various types, showing awarded teams tended to have higher total prototyping proportions.

proportion of their videos (M = 35.9%) compared with the awardee teams (M = 50.7%). We found a statistically significant main effect of awards on total prototyping proportion, $F(1, 89) = 4.088$, $p = 0.046$ (Table 3). The interaction between awards and team type was not statistically significant ($p = 0.501$). Awardee teams of all types tended to dedicate more time in their video to various types of prototypes than non-awardee teams did (Fig. 2).

3.2 RQ2: Virtual and Physical Prototyping usage in Awarded Teams

In general, there was more use of virtual prototyping methods when compared with physical prototyping methods across all teams. 3D CAD models and system diagrams were the two most used prototyping methods. Electronic CAD models and 2D drawings were the least common virtual prototyping methods used, while physical sketches were the least used prototype in general. We found that non-awardees displayed virtual prototypes for a similar proportion of their videos (M = 28.3%) compared with the awardee teams (M = 30.8%). In contrast, we found that awardees displayed physical prototypes for a larger proportion of their videos (M = 19.95%) compared with the non-awardee teams (M = 8.63%). We identified a significant main effect of awards on physical prototyping proportion, $F(1, 89) = 7.964$, $p = 0.006$ (Table 4). The interaction effect between team type and awards were not statistically significant ($p = 0.719$, respectively).

3.3 RQ3: Discipline-specific Prototyping Patterns

Team type was an important factor in the total prototyping proportion of teams. We found a statistically significant main effect of team type on total prototyping proportion, $F(4, 89) = 2.923$, $p = 0.025$ (Table 3). However, for physical prototyping, we did not identify a significant main effect for team type, $F(4,89) = 1.213$, $p = 0.311$ (Table 4). The physical prototyping patterns for various team types were similar with a high amount of variation. Table 5 and 6 show the average and standard

Table 4. Results from two-way ANOVA for physical prototyping proportion

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
(Intercept)	0.993	1	0.993	53.461	0.000
TeamType	0.090	4	0.023	1.213	0.311
Awards	0.148	1	0.148	7.964	0.006
TeamType * Awards	0.039	4	0.010	0.523	0.719
Error	1.653	89	0.019		

Table 5. Average time in seconds and standard deviation of time dedicated to each physical prototype category by different team types

	Physical sketch	Physical model	Physical model demo
Aerospace (n = 6)	0 (SD = N/A)	39.5 (SD = 28.97)	66.5 (SD = 62.7)
Mechanical (n = 24)	8.5 (SD = 3.5)	73 (SD = 72.21)	39.38 (SD = 32.4)
Biomedical (n = 6)	103.5 (SD = 90.5)	37 (SD = 12.05)	23.67 (SD = 17.25)
Interdisciplinary (n = 37)	35.29 (SD = 21.45)	39.73 (SD = 20.86)	46.06 (SD = 27)
Electrical (n = 14)	36 (SD = 0)	88.67 (SD = 118.96)	68.75 (SD = 36.2)
Chemical (n = 18)	0 (SD = N/A)	27.67 (SD = 12.36)	41.25 (SD = 27.33)

Table 6. Average time and standard deviation of time dedicated to each virtual prototype category by different team types

	CAD model	CAD simulation	CAD demo	2D Dwg	Electrical CAD	Virtual sketch	System diagram	Soft. demo	Soft. screenshot
Aerospace (n = 6)	109.17 (SD = 61.87)	32.75 (SD = 23.78)	56 (SD = 33.04)	0 (SD = N/A)	0 (SD = N/A)	0 (SD = N/A)	26.33 (SD = 16.21)	46 (SD = 0)	47 (SD = 0)
Mechanical (n = 24)	83.95 (SD = 50.48)	44.88 (SD = 33.39)	42.5 (SD = 25.3)	13.4 (SD = 10.84)	21.17 (SD = 7.95)	22.5 (SD = 8.5)	50.75 (SD = 25.73)	65.43 (SD = 46.45)	43.89 (SD = 14.51)
Biomedical (n = 6)	74.75 (SD = 70.75)	21 (SD = 0)	0 (SD = N/A)	21.67 (SD = 13.91)	25 (SD = 0)	37 (SD = 0)	42 (SD = 23.9)	44 (SD = 24.09)	34 (SD = 15)
Interdisciplinary (n = 37)	60.77 (SD = 46.73)	46.33 (SD = 26.57)	74.33 (SD = 46.35)	61 (SD = 38.22)	38 (SD = 35.02)	67 (SD = 0)	57.76 (SD = 47.12)	75.28 (SD = 65.41)	46 (SD = 33.85)
Electrical (n = 14)	64 (SD = 45.01)	58 (SD = 0)	0 (SD = N/A)	21 (SD = 4)	0 (SD = N/A)	0 (SD = N/A)	55.08 (SD = 23.69)	67.11 (SD = 44.24)	29.2 (SD = 18.85)
Chemical (n = 18)	33 (SD = 0)	0 (SD = N/A)	79 (SD = 0)	0 (SD = N/A)	0 (SD = N/A)	0 (SD = N/A)	91.06 (SD = 64.04)	33 (SD = 7)	28.67 (SD = 11.44)

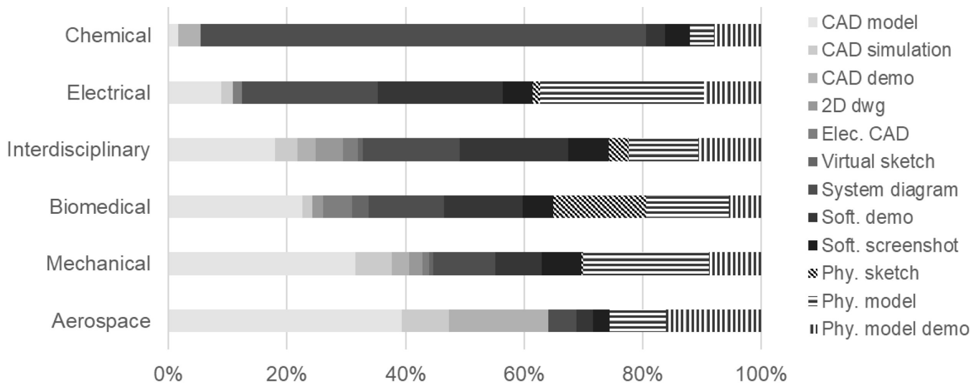

Fig. 3. Comparison of different prototyping methods for the different team types.

deviation of time that was dedicated to each type of prototype (physical prototypes in Table 5, virtual prototypes in Table 6) for each team type.

Because each team had varied video duration, we also compared the percentage of time dedicated to each prototyping category (calculated by dividing the time dedicated to each prototyping category by the sum of the time dedicated to all prototypes). This data is shown in Fig. 3.

There are several differences with the distribution of virtual prototyping usage among all disciplines. Aerospace teams relied heavily on CAD demonstrations for visual communication in comparison with other disciplines. Chemical teams had the lowest percentage of CAD models with no use of simulations and demonstrations; however, they exhibited a heavy dependency on system diagrams accounting for over 75% of total prototyping methods used. Only aerospace, mechanical and interdisciplinary teams made use of CAD demonstrations as visual communication. Interdisciplinary teams had the highest percentage of 2D drawings used. Aerospace, electrical and chemical teams made no use of 2D drawings and virtual sketches. All teams had a similar percentage use of software screenshots.

Perhaps reflecting the interdisciplinary nature of the biomedical engineering major, biomedical and interdisciplinary teams presented a similar distribution of prototyping methods, with interdisciplinary teams having a slightly lower usage of physical prototypes. Interdisciplinary teams had more diverse prototyping usages than other teams, with use of all prototype types observed in at least one team.

Mechanical, biomedical, and electrical teams exhibited a higher usage percentage of physical prototyping methods. Electrical teams in particular had the highest percentage of physical prototypes overall, perhaps reflecting how often integrated electric systems and sensors were often featured in the videos. Chemical teams on the other hand presented the least amount of physical prototypes by a considerable amount. Biomedical teams had the highest use of physical sketches by far in contrast to other disciplines. Physical model demonstrations were used evenly among all disciplines excluding aerospace and biomedical teams which had a larger and lower use respectively. Aerospace teams presented the highest percentage of physical prototyping demonstrations among every discipline, largely in recordings of design, build, fly projects. This unique distribution of prototyping use across all disciplines reflects the diverse project requirements and characteristics.

3.4 Additional Observations

We observed that many groups used many of the same visual elements in their video as what was required as deliverables in the capstone course. For example, each team was required to design a poster, and the majority of teams (65.7%) included an image of their poster in the video, despite the fact that it was hard to read poster text or interpret poster images in the video format. Similarly, project requirement tables, acceptance test plans, system block diagrams, and budgets were listed as part of the written final report template provided to students, and many teams presented these same elements in their video. Drawings and other design documentation were also included in their written final report template, but less specific instructions about the formatting and presentation of these elements were provided, which may have led to variation in how teams interpreted the requirements and the extent to which they felt it was necessary to include these elements in their project videos.

Many of the teams mentioned that their progress on their design, especially related to fabrication, was significantly impacted by the COVID-19 pandemic. These students began their design process in Fall 2019 and finished in Spring 2020, so much of their final prototyping and design was conducted under pandemic lockdowns. At the studied institution, the students were allowed to continue accessing campus fabrication and assembly spaces in small groups, but many students said that delays and difficulties in accessing spaces prevented them from making expected progress.

4. Discussion

Analysis of our data suggests that awardees showed more use of prototypes as visual communication aids. This finding supports common guidance that prototypes can aid communication [12, 20, 21]. However, our dataset does not allow us to understand causation i.e., if awardees were successful at earning awards because of their effective use of prototypes for communication. It is certainly possible that teams that earned awards tended to have been more successful at creating prototypes (especially physical prototypes) during the design process, and therefore had more prototypes available to use as visual aids. We were not able to collect data on the total number of prototypes that teams may have created throughout the course, as we were only able to extract information about the prototypes teams chose to share in their final presentations.

Because our data were observational and not from a controlled experiment, there are external factors that may influence our results. For example, students were given guidance for how long to make their videos. These time limitations in presentation may have meant that teams were not able to share all of the prototypes they developed, and so our dataset is likely not a perfect reflection of how many prototypes were actually produced during the design process. Because the videos are not necessarily a perfect representation of all prototypes made during the design process, it is possible that students prioritized presentation of virtual prototypes over physical prototypes, perhaps because they were viewed as being more effective for communicating progress. Our dataset cannot tell us how common the use of virtual prototypes was during the design process itself. Teams that shared more physical prototypes than others may also have created more virtual prototypes than others, so our results do not necessarily suggest that the *construction* of physical prototypes was correlated with success.

Another limitation of this study is our use of awards as a metric of success. While effective communication is certainly needed for student teams to earn awards, there are other significant factors affecting which teams earn awards, including fit for the offered awards and biases of judges. Physical prototypes may be viewed more favorably than virtual prototypes by judges, for example. Also, student teams' success at developing a design solution that meets the project need is also affected by the scope of the project and effective communication with sponsors. Future work will focus on identifying more holistic and unbiased measures of success and communication effectiveness in the context of capstone projects.

Although the above limitations restrict our ability to conclude with certainty, we posit there is a relationship between actual prototyping usage and prototypes presented in the videos, as it is logical that teams would want to include as high fidelity of representations of the actual design as possible to demonstrate their progress on the design. We may also assume that teams who created more prototypes in general were able to select the most effective prototypes for communication purposes to include in their final presentations.

It is important to note that design teams' goals for communication vary throughout a design process. For example, as a design process advances, designers may use prototypes "visualize and explain concepts, show forward progress and accountability, and then gather feedback and negotiate features" [12]. The most effective prototypes for the end-of-course presentations we analyzed in this study are not necessarily the same as those that may have been used earlier in the design process. Although we saw differences among awardees' use of physical prototypes and not virtual prototypes during these final presentations, virtual prototypes could still be useful for early communication and learning.

We hypothesize that total prototyping percentage was associated with awards for this year because teams with more prototypes were better able to complete their design, even with COVID-19 disruptions. Some teams had hardly any visualization of their final design beyond theoretical sketches and system diagrams. Without visual representations of the final, complete design, it was likely difficult to convince judges and sponsors that the team had successfully met their project requirements. In general, awardees tended to have more physical prototypes than non-awardees (although the significance for this effect was just outside our significance level), which is again a potential indication that awardee teams were better able to make progress and conduct more fabrication during COVID-19 disruptions.

Our results have several implications for engineering educators. Regardless of major, our study supports the practice of encouraging student design teams to create prototypes, with a particular focus on physical prototypes. Based on our results, prototypes of many forms can make effective communication aids for student projects. In coursework, more emphasis can be given to engineering students to view prototypes as communication tools rather than purely as proof of concept or means to enable testing.

Recommendations for prototyping for communication are likely discipline specific, to some extent. We observed distinct prototyping behavior depending on the discipline makeup of a team. For example, teams with chemical engineering projects did not frequently present CAD models and instead frequently used system diagrams to represent their designs. The requirements of different projects and expertise of team members likely affected the prototypes employed by each team.

It is difficult to separate what each discipline is trained to do versus what the most effective prototyping method may be for that discipline. Presumably, educators are likely to train students on the most useful prototypes for their discipline, but it is possible that lack of awareness of new tools or the benefits of some prototyping methods could lead to ineffective prototyping or communication use. Prior studies have indicated that students' choice of virtual communication tools is guided by familiarity in addition to functionality and practicality [9].

Interestingly, there were some teams that had nominally similar projects (e.g., mechanical and biomedical) that still seemed to have distinct prototyping usage, potentially driven by exposure to CAD tools (e.g., biomedical engineering students at this institution are not required to take a dedicated CAD course while mechanical engineering students are). This suggests that exposure to a range of prototyping modalities for disciplines likely to work in interdisciplinary teams can support more robust collaboration and communication amongst team members.

This paper presents several areas for future work. Our dataset is drawn from an interdisciplinary capstone course and it may be that our results are unique to interdisciplinary teams, to some extent. Even in teams we categorized as mechanical teams, there was typically a mix of student majors. A follow-on study could compare prototyping usage in final projects for a mechanical engineering course and compare their usage to that of the mechanical teams in our dataset. Another attribute of our dataset is that it was drawn from a year with a significant COVID-19 disruption. Our results, such association between awards and proportion of final presentations with visuals of prototypes, may be unique to this particular year. In future work, we hope to analyze other years of data to see if our results are unique to the 2019–2020 school year.

5. Conclusion

In this study, we identified physical and virtual prototype usage frequency and patterns among awardees and non-awardees across different engineering disciplines from final deliverable video presentations of an interdisciplinary capstone course conducted among COVID-19 disruptions in the 2019–2020 academic school year. We found a larger proportion of prototyping usage among awardees compared to non-awardees. The main effect for awards on physical prototyping approached statistical significance, while there was no difference in proportion of virtual prototypes displayed. Despite the important connection between physical prototyping and success that has been reported in literature, we observed more usage of virtual prototyping methods when compared to physical prototyping methods across all teams. However, there were unique distributions in prototyping usage patterns between each discipline, with chemical and electrical engineering teams infrequently using CAD or physical prototypes. Our findings illustrate and support the significance of visual artifacts and prototypes as means of communication in engineering projects, especially virtual communication, and provide guidance for student designers to successfully convey the design process in video format.

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Pablo Luna Falcon is an undergraduate student majoring in mechanical engineering at the University of Arizona. He serves as a mentor for the Arizona's Science, Engineering and Math Scholars Program where he guides underrepresented students in the development of skills to navigate academic and professional obstacles in college. With his research he is interested in exploring novel multiscale manufacturing strategies and finite element methods to enable scalability of engineered devices and materials. He plans to pursue a PhD in Mechanical Engineering or Theoretical and Applied Mechanics.

Hannah D. Budinoff is an Assistant Professor of Systems and Industrial Engineering at the University of Arizona. Her research interests include additive manufacturing, geometric manufacturability analysis, design for manufacturing, and engineering education. She completed her PhD in 2019 in mechanical engineering at the University of California, Berkeley, where she was awarded an NSF Graduate Research Fellowship. She is the recipient of a 2021 American Society for Engineering Education Educational Research and Methods Division Apprentice Faculty Grant.

Julia Kramer, MPH, PhD, is an Assistant Professor in the Department of Mechanical Engineering at the University of Michigan. She received her BS in mechanical engineering from the University of Michigan and completed her PhD in mechanical engineering and her master's in public health at the University of California, Berkeley. Her research focuses on engineering approaches to support social justice and promote equity, particularly through the development and investigation of products, services, and systems that improve access to health care in low-resource settings. She also studies and teaches human-centered design methods that support diverse participation in equity-oriented work.

Jannatul Bushra, Jannatul Bushra is a PhD student at the Department of Systems and Industrial Engineering at the University of Arizona. She received her MS in Industrial Engineering from the same department in 2022. Before joining the University of Arizona, she received her BSc in Industrial and Production Engineering from Bangladesh University of Engineering and Technology, Bangladesh. Her research interests lie in applications of optimization and data science tools in design for additive manufacturing and enhancing the skills of engineering students through innovative teaching methods.