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Abstract

A cube satellite (CubeSat) is a small (10 cm X 10 cm X 10 cm) cubic form factor device that continues to gain in popularity due to its low mission costs and accessibility. As of 2021, over 1,600 CubeSats have been deployed into low-earth orbit, many of which are educational in purpose. According to BIS Research, the global small satellite market is expected to increase from $0.52B in 2018 to $2.9B by 2030. Maine is a sparsely populated, largely rural State with historically low rates of representation in STEM related fields. Maine has placed in the bottom third of U.S. states in STEM workforce size, conferred STEM degrees and STEM economic output in recent years. Yet, there exists significant opportunity for CubeSat launch services from Maine due to its geographic access to polar launch operations vital for telecommunication, weather and earth mapping satellites. Numerous initiatives are being developed to grow the Maine space-based economy, all of which recognize the importance of Maine workforce development and STEM preparedness in K-12 education.

To bridge the technological gap, the University of Southern Maine has developed a CubeSat design competition targeting grade 6-8 and 9-12 students to engage participants in collaborative STEM learning. In this program, teams of 1-15 students from school districts across Maine create a unique science or technology demonstration mission and use the engineering design process to design and build a CubeSat meeting the mission requirements under cost, performance and time constraints. Teams are judged on their mission success and ability to communicate results to a broad audience. Teams are provided learning workshops in the design process, computer-aided design, computer programming and fundamental science during the competition. Methodologies, outcomes and assessment tools are presented and a framework for future expansion is provided.

1.0 Introduction

The global space industry produced a total economic expenditure of USD$428 Billion in 2019 according to the Space Foundation [1]. The U.S. represents a sizable portion, USD$64 Billion, of this economy [2]. The total gross economic impact output is estimated by the U.S. Department of Commerce to be USD$195 Billion, providing a 3:1 impact to the local economy and supporting 354,000 jobs [3]. The economic forecast for the US space industry is bright. The global bank, Morgan Stanley, released an economic projection of a $1 Trillion global space economy by 2040, with the US playing a leading role [4].

The rapid space industry growth in the U.S. has led States and organizations to develop strategic plans to address the emerging needs for talent and services. The State of Maine, for example, who is home to number of small businesses currently servicing the space industry, is considering investment to develop a Maine Spaceport Complex to act as an economic center and service provider to industry and the public. Maine is the most northern State on the US east coast and reaches to 47 degrees latitude making it a candidate launch site for polar orbits. Maine is sparsely populated and largely with historically low rates of STEM participation [5]. For example, Maine has traditionally ranked in the bottom third of US states in terms of STEM workforce size, economic output and graduation rates according to the U.S. National Science Foundation [6]. In 2020, the percentage of Maine individuals working in STEM was 6.78% compared to the national average of 9.23%. To address these concerns, the State identified seven target technology areas for investment including biotechnology, advanced materials, composite engineering, forestry and marine technologies, environmental science, precision manufacturing and information science. Proponents of the Maine Spaceport Complex point out the strong alignment of the future space economy needs with existing target technology investments.

To meet the anticipated long-term workforce demands, strategic efforts are underway to develop STEM skills and general space industry awareness within Maine's youth population. As a catalyst, cube satellites (CubeSats) have been identified as a preferred medium to provide students with a hands-on learning experience across a wealth of space-based science missions. CubeSats are a class of nano-sized satellites that confirm to a 10 cm X 10 cm X 10 cm form factor. This basic form is classified as a one unit (1U) CubeSat. Additional form factors can be created from this basic shape such as a 20 cm X 10 cm X 10 cm (2U) or a 30 cm X 10 cm X 10 cm (3U) satellite. CubeSats are demonstrated to be accessible and engaging to K-12 STEM learners, have a low cost barrier to entry and offer a breadth of skill development opportunities [7]. Examples of successful K-12 skills development topics include, but are not limited to, computer science, data science, robotics, space science, project management, engineering design process and physics. As such, numerous K-12 programs have been developed nationally, ranging from summer camps to embedded classroom learning curriculums, in order to meet diverse learning outcomes [8-12]. Further, CubeSats continue to receive national interest from the scientific community for their growing use as primary and support mission capabilities. According to BIS Research, the global small satellite market is expected to increase from $0.52B in 2018 to $2.9B by 2030 [13].

In this paper, we present evidence for the successful use of a competition-based CubeSat design program targeting Maine youth in grades 6-12 over the years 2021-2022. The goals of the program are four fold:

1) Engage students in STEM experiential learning and consider future careers within the space industry.
2) Increase student confidence in STEM through problem solving within a real space mission experience.
3) Allow students to develop and practice soft career skills, such as teamwork, leadership and project management
4) Bolster the CubeSat research and development work being undertaken within the Maine space industry.

Competition (challenge) learning is an effective tool for motivating students for STEM learning [14-17]. In addition, the authors hope a by-product of the competition format will be stronger connections between educators and learners from peer institutions across the State.

The competition requires teams to develop a space-based technology or science mission of their choosing for a 1U CubeSat based on an Arduino Uno microcontroller platform. Teams are provided identical Arduino sensor kits and are tasked with identifying suitable additional hardware and software within cost, weight and volume constraints, meeting their unique mission objectives. A total of 15 hours of virtual learning content are provided to motivate and guide learners through multiple skill development modules. Teams then submit a preliminary design report (PDR) detailing their designs, their mission success criteria and operational plans for competition judging. Finalists are invited to the University of Southern Maine to build their designs and test them prior to a high-altitude balloon launch.

2.0 Methods

2.1 Recruitment

Maine is home to 136 public and 72 private high schools and an estimated 441 middle schools. Flyers advertising the competition with registration information were broadly disseminated to each administration office for distribution to teachers. Flyers were also sent directly to the science, math and technology faculty for which public information was available. Teams consist of at least one student and one teacher or parent within two grade groups; middle school (grades 6-8) and high school (grades 9-12).

Registration is free to all teams, regardless of financial ability or previous space technology preparation. Registration consisted a google form capturing teacher name, address, phone number, team size and team name. Registrants were also asked to comment on their perceived preparedness level for the competition and their initial concerns areas.

Upon registration, each team is provided a commemorative 1U CubeSat chassis which was 3-D printed using polylactic acid (PLA) with support from the University's Maker Innovation Studio

(MIST). The completed chassis are shown in Figure 1. Each team also received an Arduino-based sensor kit valued at approximately USD$100. A table of equipment is provided in Table I.

Table I: Arduino based 1U CubeSat Components Provided at Registration

Component	Manufacturer	Model
Micro-controller	Arduino	Uno Rev. 3
Base shield	Arduino	V2.0 for Uno Rev. 3
USB cable	Arduino	Type A/B
Universal wire connector	Arduino	4-pin grove
Temperature and Humidity Sensor	Seeed Studio	DHT11
Precision Barometer	Seeed Studio	DPS310
6-axis Accelerometer	Seeed Studio	LSM6DS3
Volt Meter	Astro AI	AM33D
MicroSD breakout	Generic	Amazon B07PFDFPPC
Battery Pack	Adafruit	3788

Figure 1: 3-D printed 1U CubeSat chassis provided to competition registrants. Corner rings provided as high-altitude balloon attachments. Photograph courtesy of So Young Han.

A total of 10 teams registered for 2021 competition and 20 teams registered for the 2022 competition totaling 182 students across all grade groups. Team sizes range from 1-13 students with 8 teams in the grade 6-8 group and 22 teams in the grade 9-12 group. Teams are primarily located within Maine's coastal regions representing urban/suburban population centers. Teams consist of a blend of after school clubs and in-classroom learning groups.

Upon entering the design competition, all participants are given a four-level, Likert pre-workshop survey to acquire biographical information and assess preparation, STEM interest, and likely career path. A total of 36.7% of participants (n = 44) responded to the questionnaire. Participants reported an age range from 12-17 with a median age of 15.4 and are 68% male, 27% female with the remaining either non-binary or choosing not to report. A full list of questions and responses can be found in Section 4.1.

2.3 Workshop Program

A total of 15 hours of motivational and skills development content was provided to the competition participants in five, 3-hour, live, virtual workshops which ran bi-weekly on weekend mornings. Content was recorded and archived for teams wishing to interact asynchronously. Delivered content consisted of mini-lectures/workshops lasting 30-60 minutes in duration. A summary of each workshop agenda can be found in Table II. Each mini-lecture/workshop targeted a skill development area; such as programming, computer aided design, engineering design process, etc. Each virtual workshop also introduced a guest speaker from industry or education to provide perspective to the student. Guest speakers included current and former NASA engineers. Workshops also highlight current NASA space missions, such as the James Webb Space Telescope (JWST), which launched during the workshop series and provided excellent case studies on engineering design and mission planning.

Workshops were available to all teams in a single live event every two weeks. As such, teams had opportunity to interact and provide/receive peer feedback. The beginning of each workshop was devoted to team updates where each team provided an informal status report detailing recent progress and challenges. This period also allowed teams to ask questions related to prior workshop content.

A breakdown of the time devoted to various skills development content over the course of the workshop series s provided in Figure 2. Most of the workshop was devoted to software programming and space technologies. Programming was identified early in the workshop series as an important skills development area based on teams initial skill demonstration. A majority of students reported familiarity with programming, but lacked basic understanding related to Arduino programming and hardware/software interfacing. Therefore, each workshop offered 40-60 minutes of Arduino specific programming utilizing various functionalities of the provided kit. By the end of the workshop series, each team was guided through the hardware setup, programming, data acquisition and data formatting of the sensors within their Arduino-based kit provided at registration.

Table II: Summary of daily content delivered to learners in virtual live workshops

	TOPIC DESCRIPTION	SPEAKER	TIME (MIN)
WORKSHOP #1	Introductions and Pre-Survey	USM Faculty	20
	Engineering Design Process	USM Faculty	20
	Space Mission Overview	NASA Speaker	25
	Project Management	USM Faculty	20
	Space Mission Planning	USM Faculty	25
	Arduino Programming	USM Staff	60
WORKSHOP #2	Team Updates	All Participants	30
	The Space Environment	USM Faculty	30
	SmallSats for Education	NASA Speaker	30
	Ideation	USM Faculty	20
	Arduino Programming	USM Staff	60
WORKSHOP #3	Team Updates	All Participants	15
	Introduction to CAD	USM Faculty	45
	NASA Engineering (JWST)	NASA Speaker	45
	Arduino Programming	USM Staff	55
WORKSHOP #4	Team Updates	All Participants	15
	Introduction to CAD	USM Faculty	45
	Thermal Engineering	USM Faculty	25
	Electrical Power	USM Faculty	25
	Arduino Programming	USM Staff	50
WORKSHOP #5	Team Updates	All Participants	15
	CubeSats around Mars	NASA Speaker	45
	Attitude Determination and Control	USM Faculty	25
	Radio Communication	USM Staff	25
	Arduino Programming	USM Staff	50

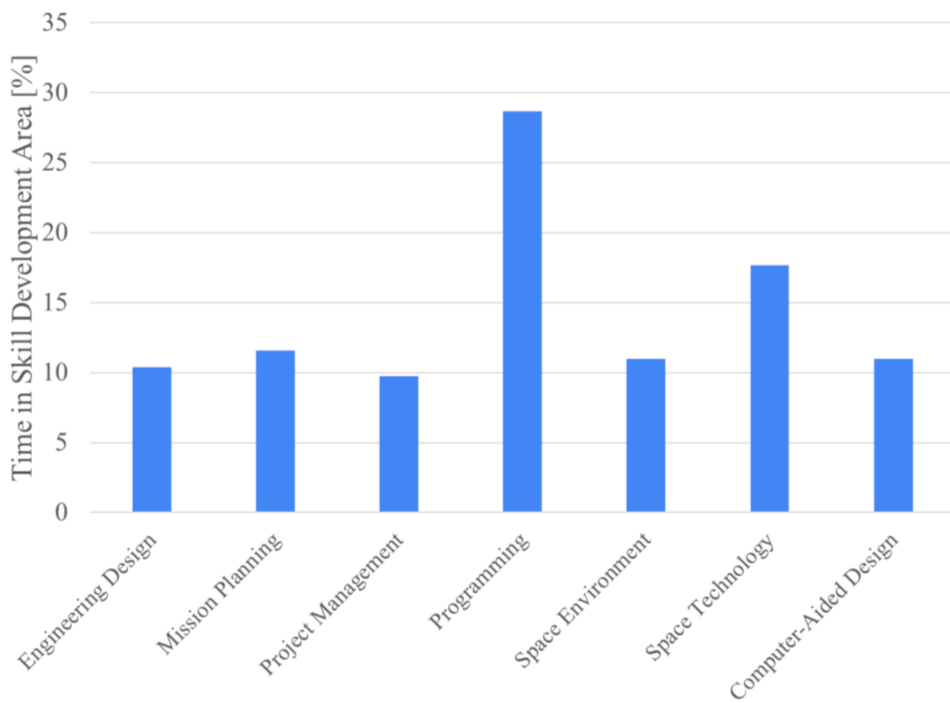

Figure 2: Breakdown of time devoted to skills areas during training workshops.

3.0 Competition Format

3.1 Constraints and Specifications

The CubeSat design competition is to design a payload system for a 1U Cubesat that can perform a science or technology based mission of their choosing. The designs must meet the following basic mission requirements.

1) Must meet the 1U CubeSat design volume form factor of 10cm X 10cm X 10cm (61 in^3)
2) Must weigh less than 1 kg (2.2 lbs.)
3) Must be include its own on-board power
4) Must contain an externally actuated electrical power switch
5) Must survive a fall from 3 feet (0.91 m) in earth's gravity
6) Must be capable of operating in conditions over 90,000 feet (27.7 km)
7) Must be water resistant in case of a water landing
8) Must be constructed with a total cost less than $700
9) Must have clearly identified and measureable mission objectives to judge success.

The registrants are judged on the overall quality of submitted designs packets, creativity and uniqueness of the chosen missions and anticipated benefits to the scientific and engineering communities.

3.2 Competition Deliverables

The competition is separated into two main phases: phase A) research & design culminating in a preliminary design review (PDR) report, and phase B) build, test and launch culminating in a high altitude balloon launch.

3.2.1 Phase A

In the research & design phase, teams identify a science or technology demonstration mission and conceptualize, develop and detail their designs for phase A judging. Conceptual designs packets are developed and submitted for judging. Phase A activities lasts 3 months and runs concurrent with the skills development workshops. At the conclusion of phase A, three finalists from each grade group will be selected to progress to the build & test phase, along with 1-2 at large bids. Below are specifications required of the conceptual design package for the high school group. Middle school participants are required to submit a similarly formatted design concept packet, but reduced word count and flexibility of presentation style is afforded.

- A mission title
- Team members and responsibilities
- 200 word executive summary
- 2000 word full proposal that explains,
    1. Mission Problem Statement

2. Mission Objectives
3. Team Roles and Responsibilities
4. Conceptual Design
5. Operational Details
    1) On-board power details
    2) Data recording
    3) Mission execution procedure
6. Budget including a bill of materials (BoM)
7. Compliance
8. Scientific Merit

3.2.2. Phase B

Finalists advancing to phase B enter the build and test phase. Working from the mission proposals received in phase A, the competition procures the specified hardware, which is sent directly to the participants. Finalist teams have four months to complete the build and test of their devices ahead of the scheduled high-altitude balloon launch. During this time, finalists are invited to USM's Maker Innovation Studio (MIST) to work directly with University personnel to construct, program, test and certify the operation of their CubeSat prior to launch.

Figure 3: Photograph of high school team members assembling a deployable solar sail 1U CubeSat during the 2021 design competition. Photograph courtesy of Dr. Asheesh Lanba

Launch services are provided by the University of Maine's High Altitude Ballooning Club. For the 2021 competition, launch location was USM's Lewiston-Auburn College located in Lewiston, ME. On launch day, teams report to location with their pre-fabricated CubeSats. The external panel of judges interviews them prior to launch. Participants are allowed one (1) week to process and analyze their recovered mission data for submission to competition judges.

3.3 Judging

The submissions are judged first on the quality, depth and rigor of the work presented and secondly by the breadth of the work in terms of topics covered. The judging panel consist of volunteer industry and academic experts with prior knowledge and experience in space mission planning and CubeSat development. Judges with a reported conflict of interests (e.g. a parent of a participant, etc.) are recused from deliberating on that teams score.

Judging for phase A reports occurs in two rounds, the first round is a triage in which final design submissions will each get approximately a 10-minute review from at least 3 judges in a closed envelope format. Judges score the teams for both scientific merit (0-10) and overall quality (0-10) as shown in Table III. An overall combined score (0-20) from each triage judge is then aggregated. Team scoring a composite score of 8 triage points or greater are deemed "successful" in meeting the CubeSat design mission proposal requirements. The Top 8-10 scoring submissions from the grade 6-8 and grade 9-12 groups will then move to the "semi-finalist" judge committee.

In the "semi-finalist" round, judges are asked to provide a new 15-20 minute review of each remaining submissions. The judges then go to open committee to discuss the applications. Through this process the top 3 teams are awarded "Finalist" submissions for each age group and the remaining applicants are given "semi-finalist" awards.

At the conclusion of the build-off round, launch and recovery, the judges review the assembled CubeSat designs, the data gathered during launch operations and interview the teams. Teams are judged on build quality, functionality of the designs and adherence to mission success criteria. Judges award a "Best in Show" for the CubeSat which most exceeds the basic performance requirements of the competition, a "Runner-Up" CubeSat award and an "Overall Competition Winner" in a deliberation format. The Overall Competition Winner is expected to meet or exceed all, or most, of the mission success criteria outlined in the project proposal and demonstrate an above average build quality.

Table III: Example CubeSat competition triage judge scoring rubric. Composite scores of 8 or greater achieve a "successful" mission proposal.

School name:____XYZ Team______________ Grade Group: _x_ 6-8 __9-12

Check One: __X_ Successful ___ Unsuccessful

QUALITY	Score (0-2)	Written Comments
Adherence to Competition Rules: Submission sections found and complete. No extraneous information. Budget <$700	1	Meets requirements. Some bill of materials information missing
Professional Format: Submission of professional quality, good grammar and well formatted images/figures.	1	Met expectations
References and Citations: Proper citations provided to external resources and images pulled form websites.	0	None provided
Demonstrated Understanding: clearly articulated mission objectives and goals.	2	Well articulated mission and goals. Approach well thought out
Engineering Design Process: Evidence of the use of the engineering design process in decision making.	1	Conceptual design path demonstrated with evidence of improvement

SCIENTIFIC MERIT	Score (0-2)	Written Comments
Components/Technology: Clearly demonstrated understanding of basic component operations and limitations.	1	Basic understanding demonstrated
System Integration: Clearly demonstrated system capabilities and cubesat packaging	1	Basic cubesat assembly provided
Success Criteria: Clearly identified mission success criteria and are reasonably achieved within the competition format.	0	Mission success metrics not clearly identified.
Broader Impacts: Clearly identified community and scientific benefits within context of recent events.	2	Demonstrated understanding and provided case study examples
Novelty: Approach and methods demonstrate novelty or uniqueness showing originality of thought.	1	Some technology assembly required original approach

TOTAL SCORE out of 20 = __10_____ Important science goal, Lacking details overall_

4.0 Results and Discussion

4.1 Entrance Data

Pre-workshop surveys aimed to assess student preparedness and their confidence in an array of technical content areas. A summary of questions and responses are provided in Table IV. The survey questions were determined valid using critical value testing by Pearson's correlation coefficient at 95% confidence interval. All question, with the exception of question 1, obtained a correlation above the critical value, 0.2512, for single tail multivariate correlation with 42 degrees of freedom. Question 1, however, showed a correlation of approximately zero. This result is consistent with almost all respondents reported "very likely" to attend college upon graduation (3.77/4.00). Further, respondents are more likely than not to pursue STEM careers after graduation. Despite this high level of STEM interest, respondents also report being “unsure” or “not confident” when asked about space industry careers, space characteristics or mission planning. Yet, respondents felt adequately prepared to undertake the CubeSat design competition.

Respondents reported a moderate level of confidence in the targeted STEM categories of programing, space environment and mission planning. Further, respondents reported a moderate level of confidence in their understanding of the industry. These results were consistent across both male and female respondents as well as high school and middle school.

Table IV: Entrance survey questions and responses of the CubeSat design competition (n = 44)

Q#	Formulated Question	Result* (Ave.)
1	How likely are you to enter college upon graduation?	3.77
2	How likely are you to pursue a career in Science, Engineering or Mathematics?	3.61
3	How likely are you to consider a career within the space industry?	2.66
4	How well prepared do you feel to undertake this competition?	2.73
5	How confident are you in explaining a CubeSat to a peer?	2.86
6	How confident are you in explaining the engineering design process to a peer?	3.02
7	How confident are you in explaining the primary components of a CubeSat to a peer?	2.50
8	How confident are you in explaining careers in the space industry to a peer?	2.45
9	How confident are you in explaining project management to a peer?	2.80
10	How confident are you in explaining mission planning to a peer?	2.48
11	How confident are you in explaining the characteristics of space to a peer?	2.61
12	How confident are you in explaining the function of basic sensors to a peer?	2.77
13	How confident are you in explaining computer-aided design to a peer?	2.73
14	How confident are you in explaining basic programming to a peer?	2.47
15	How confident are you in explaining basic electronics to a peer?	2.91

*1 = unlikely/poor, 4 = very likely/very confident

4.2 Workshop Success

The CubeSat design workshop series is shown to be an effective tool to improve student confidence in STEM and moderately successful in building awareness of space science and technology careers. A chart showing changes in participant responses to the questions described in Table IV is presented in Figure 4 resulting from 20% response rate in the post-workshop survey. Questions 1-3 relate to the interest in college, STEM and space industry careers and show modest changes in future potential of the students. This result is attributed to a large majority of students reporting “very likely” to attend college in a STEM major pre-workshop, therefore reporting equivalent responses post workshop. The largest positive increases from respondents are related to CubeSat technology. Participants reported a 25% increase in response to the question 7 “How confident are you in explaining the primary components of a CubeSat to a peer?,” moving from “not confident” to “confident”. Questions 5 and 12, which relate to understanding of CubeSat technology, also exhibited significant improvement post-workshop.

Results were tested for significance using a two-tailed Mann-Whitney U test at a significance level of 0.05. Results showed that only questions 5, 7 and 12 exhibited statistically significant differences in student confidence pre- and post-workshop. This result indicates that the CubeSat competition workshops were successful in improving student confidence in CubeSat technology, its operations and the understanding of basic sensors used in space. The data are not conclusive in improving confidence in engineering design or programming. Increasing participant response rates in future competitions will be critical for assessing the competition effectiveness in future iterations.

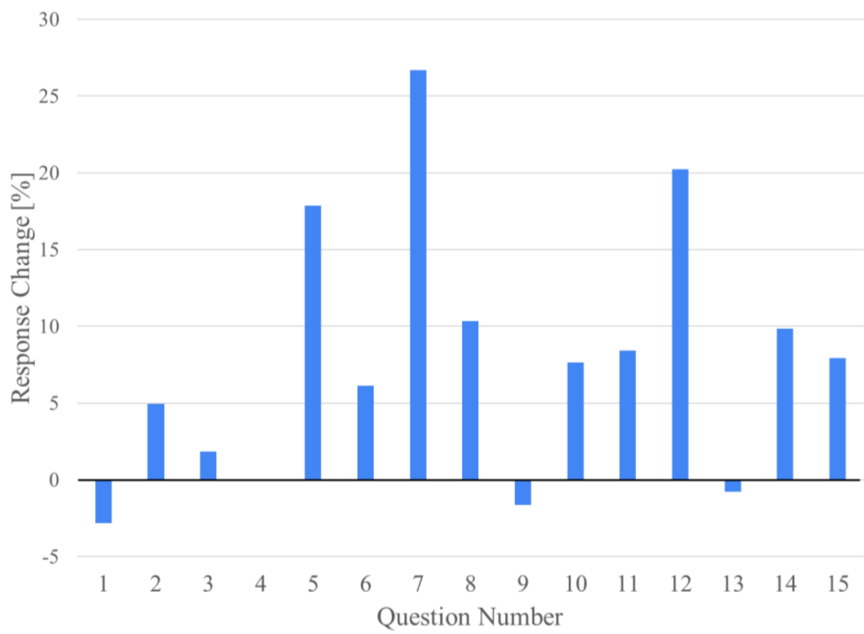

Figure 4: Change in participant answers to questions described in Table IV for post- and pre-competition workshop participation. Results for questions 5, 7, and 12 were statistically significant

4.3 Mission Proposal Results

The competition workshops successfully prepared teams for success in the CubeSat design competition. In total, thirty (30) teams registered for the competition in the first two years and resulted in twenty five (25) conceptual design (Phase A) submissions equating to an 83% team completion rate. Each team submitting a conceptual design packet was deemed "successful" by the panel of competition judges thereby achieving a 100% proposal success rate. The average score across all the teams was 12.3/20. This data includes the average score for each team across four judges, with those scores then averaged across the entire competition population.

There were two teams with an average judging score less than 8, the threshold for "successful" participation. In each case, the average score was 7.5 and saw a split between the four judges, 2 in favor and 2 not in-favor. In these cases, the panel believed that a rounded score achieved the 8 point threshold for success and the split decision was in favor of team success. In one of these cases, the school also qualified as a finalist due to low category enrollment and the team was requested to provide additional information post-judging to ensure parity with other finalist teams.

Of the five teams not submitting conceptual design packets, four of them responded in a survey that COVID-19 complications significantly impacted team success. This was particularly true for the 2021 competition, which, started as a face-to-face workshop/competition offering, and then pivoted to synchronous online programming after the first workshop due to health concerns.

4.4 CubeSat Launch Event

To date, only the 2021 competition cohort have participated in the launch event. That year, the competition launch was held on June 26th, 2021 which was open to the launch teams, family, friends, teacher mentors and judges. Nearly 60 individuals attended the event. Photographs of the high-altitude balloon launch are shown in Figure 5 describing final payloads and leaders for each CubeSat design. Prior to launch, the students are interviewed on camera by the competition organizers to gather details of their final CubeSat design, specialize components and their operation.

Figure 5: Photographs of the 2021 CubeSat competition launch event. Eight CubeSats were launched to over 85,000 ft. Photograph courtesy of Dr. Asheesh Lanba

The high altitude balloon is hydrogen-filled and supports a payload of up to 12 pounds. The balloon is equipped with a chirp, GPS tracker, two radio transmitters and camera system for observing the flight. The payload achieved an estimated 85,000 ft. of elevation over an ascent taking approximately 40 minutes. Photographs of the ascent are shown in Figure 6 showing the individual CubeSats suspended in an array just after balloon pop. The high altitude launch was an effective method of testing CubeSat design and operation for the competition. Optical systems, data recording event timing, software logic and control systems are all well supported. In the 2021 cohort, some teams opted for deployable systems, such as a solar sail or expanding solar panels, which however, were difficult to evaluate due to the high forces, air resistance and tethering of the payload system. These complications will be minimized in future balloon launches by preferential placement of devices in the payload train and use of spring tethers to reduce shock.

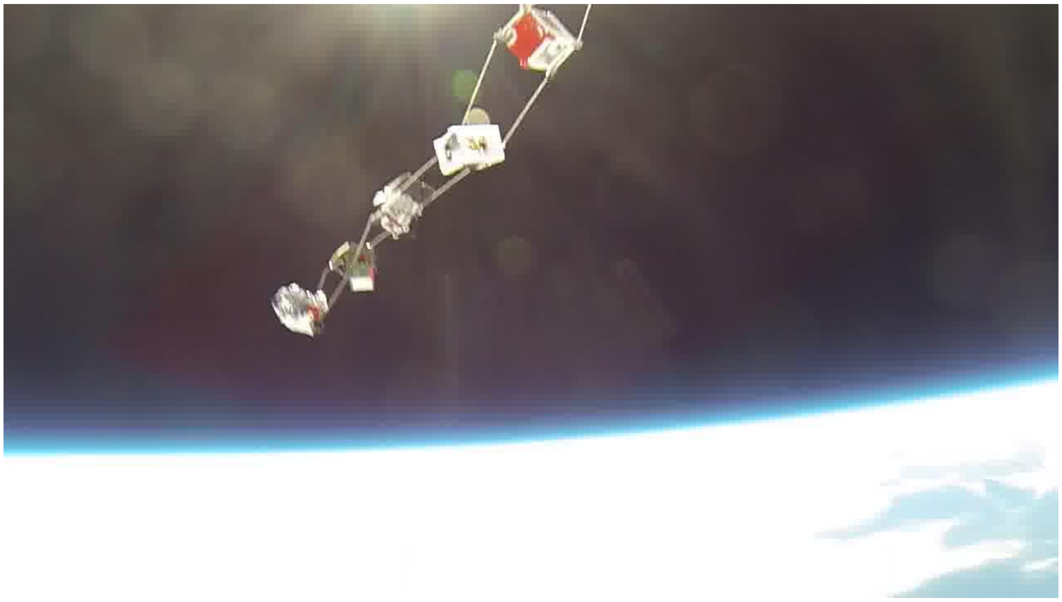

Figure 6: Photograph of 2021 CubeSat competition payloads during high altitude balloon testing. Photograph courtesy of Dr. Rick Eason.

5.0 Conclusions and Future Work

The CubeSat design competition is shown to be an effective program for increasing participant confidence in multiple STEM skills areas as well as space technology within middle and high school populations. The competition attracted over 180 students in Maine, representing 30 project teams over two years. The competition develops targeted space science and technology skills and provides awareness of space industry career options. The competition was not effective in increasing participant confidence in computer aided design or project management and will be an area of future work for the competition organizers.

Challenges of the competition include recruitment of female participants and teams from rural and low socioeconomic status regions. Each of these participant areas are currently under-represented in STEM and the competition will look to bolster their participation in future iterations. In addition, although remote synchronous workshop content improved student outcomes, the competition participants are likely to benefit from face-to-face school visits to improve the hands-on learning components of hardware assembly and programming. This approach is likely to also improve team retention in the program and increase the percentage of teams submitting mission proposals. The competition organizers are planning to develop such an approach in future interactions with the goal of achieving an equal distribution of coastal/urban and inland/rural school participants.

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