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COMMERCIAL SPACEFLIGHT OPERATIONS:
GRADUATE LEVEL CURRICULUM DEVELOPMENT

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Fostering collaboration between commercial spaceflight organizations and academia is an ongoing effort to promote advanced research and development, as well as to prepare a technically competent workforce. Achieving these goals will promote the future viability of the industry and its suppliers. Specifically, the University of Colorado at Boulder Department of Aerospace Engineering Sciences has been engaging with industry and government partners in the development of a new graduate level curriculum in Commercial Spaceflight Operations. Working in conjunction with the FAA Center of Excellence for Commercial Space Transportation, a two semester course sequence is under development, with the stated objective of serving as a bridge between theory and application, to prepare students to become real world problem solvers. Throughout this process, extensive industry and government input has been solicited to both define academic objectives and compile course content. A lecture based course, the beginning of the two-semester sequence, was first offered during the fall semester of 2011. The scope of the course includes industry background, technical requisites, launch considerations, on-orbit operations, ground requirements, mission planning, and end-of-mission concerns. This paper gives an overview of the status of the overall curriculum development, as well as the perspectives obtained from partner organizations, which can be extended to curriculum development and use within other Universities. Extensive input from industry leaders was incorporated both in curriculum formation and through guest lectures. This interaction provided perspective from industry to students that complements the academic focus delivered through traditional graduate level coursework. The first semester lecture in this two course sequence included lectures, online collaborative discussion, project assignments relevant to commercial space, and a final report on a self-selected impediment to industry growth. All of the content in this course was delivered fully accessible to non-U.S. citizens and distance learning students. The subsequent course in this sequence, which is currently under development, will provide students with lab-based operations experience and familiarize them with tools commonly used in industry. Such simulated operations experience will provide context to engineers and aid in the development of systems for increased efficiency in all sectors of the space industry.

I. INTRODUCTION

There is a growing need for academic coverage of commercial spaceflight operations topics due to the growth within both emerging and established sectors of the industry. The increasingly large commercial space industry, including both those segments already established for communication satellites and also the rapidly growing areas such as commercial crew, commercial cargo services, and possibly even beyond low-Earth orbit, drive this need. The University of Colorado at Boulder is pioneering a course within its specialized technical curriculum that aims to give future engineers a high-level understanding of the operational aspects of spaceflight, focusing on a commercially viable implementation of these practices. The goal is to bring mission designers

closer to mission operators from the very start, allowing better interaction and cooperation throughout their careers.

II. RELEVANCE

The curriculum described in this paper has been formulated in direct response to the emerging and changing needs of the space industry. As a leading educational institution in this field, the University of Colorado at Boulder sought to build upon the extensive technical coursework available to students with a course focused on the unique and ever-changing considerations of real-world spaceflight operations. There are three high level objectives of this curriculum: (1) bridge theory and application in the educational process, (2) foster and facilitate

collaboration between academia and the commercial space industry, and (3) provide a venue for dialogue and research into operational improvement for the space industry.

In working towards the first of these objectives, the curriculum outlined in this paper is designed to prepare students both as potential future operators and also as future designers of architectures or spacecraft. The absence of any established curriculum with specific focus on commercial spaceflight necessitated that an extensive trade-space be explored in preparing the future workforce in these areas. Industry feedback has indicated that high fidelity operational training is company and mission specific. Given this feedback, the curriculum is designed to provide an overview of the broad scope of the environment within which operations occur. As a graduate level engineering course, students are expected to have foundational understanding of the technical considerations, thus the curriculum is able to focus on other factors that impact or influence operations. This focus is designed to prepare students for current and future opportunities in the operations arena.

Collaboration between industry and academia has a long history of fruitful productivity in performing fundamental research and in preparing a competent and capable future workforce. The established and emerging commercial space industry has much to offer and gain from further partnerships with academic partners. Similarly, academia can learn much from working with commercially minded innovative firms. It is for these reasons that the curriculum development process seeks to foster further collaboration amongst academia and the commercial space industry. Increasing communication and improving understanding of what needs and capabilities exist within this relationship is a critical first step to broader cooperation. In response to this need, the curriculum includes extensive industry input in the academic process, student assignments, and guest lectures.

Given the technical capabilities of graduate level engineering students, there is broad potential to identify and explore current issues and future constraints on the growth and success of the commercial space industry. A beneficial attribute of the academic environment is that it contains very low risk for such studies, particularly within the context of coursework. This capability is used in conjunction with industry input to foster a critical review of topics within commercial spaceflight operations by students completing the operations curriculum. Provided the technical and operational background for such topics, students are able to study possible solutions and identify opportunities for improvement.

The broader environment within which this course and subsequent curriculum have been developed is one of both established and emerging market sectors and companies. As commercial space transportation activities in the United States increase in size and scope, it falls on the Federal Aviation Administration (FAA) to encourage, facilitate and promote safe development and execution. It is within this mandate that the FAA Office of Commercial Space Transportation (FAA-AST) established the FAA Center of Excellence for Commercial Space Transportation (COE CST). This consortium of government, academic, and industry partners has been the driving force supporting the curriculum development efforts outlined herein. As a core member of the COE CST, the University of Colorado at Boulder is managing this task.

III. INDUSTRY INVOLVEMENT

More than two dozen commercial, government, and academic organizations participated in the development of the lecture-based course. These partners, most of which are listed in Appendix I, have provided input and insight into the course outline and lecture material, as well as directly delivered guest lectures. Involvement by these organizations both helped to ensure that course content remained relevant to industry needs and that students were given the opportunity to network with contacts within the industry.

In the year leading up to the first offering of this course, all of these organizations were approached individually with draft academic objectives (and later on more detailed course outlines) and consulted for feedback. Several iterations of this process were performed, through which valuable input was gathered to improve the definition of this course. Once a rough outline of the entire course was created, a presentation was given at the 17th Annual Improving Space Operations Workshop in Boulder, Colorado. This was followed by a roundtable discussion in which many of the consulted organizations participated, as well as some new parties, to further narrow the specific goals and implementation of the course. The final academic objectives developed through these efforts can be found in Appendix II. An important piece of input received through these efforts was to clearly distinguish between human and non-human missions, due to their different nature and unique requirements. In addition, repeated encouragement was given to include systems engineering into the range of topics, due to its critical influence on all factors considered in the course. There was also the powerful suggestion of organizing the course into the structure of a program lifecycle, to “better organize the immense amount of material into

an overall flow that allows the students to always step back and see where they are in the bigger picture”. As a result, the course schedule was set up in a logical flow through five main subject areas: Background, Launch Operations, On-Orbit Operations, End-of-Mission, and Mission Planning. Mission planning here is included as the final section to allow students to first understand the components of a mission plan and then understand how they interact from the beginning of a mission. The specific topics discussed within each of these topics can be found in Appendix III. Finally, the widespread feeling appeared to be that industry partners “like the focus on Technical/Budget/Policy-legal considerations. Each of these can be very limiting, but they are not often discussed in an integrated design way”.

Industry has also become extensively involved in the development of the lab section of this curriculum to be offered in the spring semesters. Once again, industry members will serve as guest lecturers to introduce the operational procedures students will be executing during the lab projects. More importantly, however, discussions are currently taking place between the developers of the lab curriculum and industry partners to reach agreements regarding operations software donations and capabilities. Industry has been invaluable in directing the developers to the appropriate types of software required for operations during each of the stages of the mission lifetime, as well as in assisting with the actual development of simulations and modules which will be of sufficient fidelity, yet limited enough in scope for students to be able to learn and implement within the approximate three week timeframe delegated to each lab.

IV. IMPLEMENTATION/EXECUTION

The lecture portion of the Commercial Spaceflight Operations course was successfully delivered for the first time in the fall of 2011, with 19 in-class and 9 online distance students enrolled. As described in the previous section, more than 20 organizations contributed to the development and execution of this course, which led to dividing the course into five different areas related to different mission phases. Each of these broad areas included a number of individual lecture topics, some providing a broad overview of concepts and procedures and others maintaining a more technical focus, thus providing a thorough look into the issues at hand.

Because students taking the course are expected to have an aerospace background and to have been at least introduced to the required physics in their previous courses, the number of technical lectures was purposely kept at a minimum. Those that were included covered topics such as the rocket equation

and its application to launch vehicles, astrodynamics, attitude determination and control, and orbit determination. The bulk of the lectures, however, covered areas not found in typical aerospace classes. The topics of policy, financial considerations, International Traffic in Arms Regulations (ITAR), and risk mitigation and acceptance were covered in depth, having applications to several or all of the main subject areas listed above. Other lectures touched on material relating to human factors, mission design, range safety, vehicle health monitoring, ground system requirements, etc.

Throughout the semester, course content was complemented through a variety of assignments, which can be broadly broken down into research assignments and lab assignments. The first of the research-oriented assignments was weekly participation in online discussion boards with topics aligned to the material introduced during the in-class lectures. Students were expected to make thoughtful contributions to the discussions, pulling in research, experience, and opinions to delve deeper into subject matter and make direct links between lecture material and current events.

Students were also assigned a series of four mini-research projects over the course of the semester. Though these projects tended to lend themselves well as an opportunity to look deeper into a topic from in-class discussions, students were also allowed to research any topic of their choosing with applications to the commercial space industry. This freedom encouraged the students to begin making connections between their individual interests and operational applications and requirements. Research assignments were submitted as presentations, thus enabling several students to be periodically selected to present their assignments to the rest of the class.

The last research requirement for the semester was a final research project and presentation, larger in scope than those previously assigned, for which students were given the option of expanding upon their earlier research or investigating a new topic altogether. The intent of the final project was for students to gain a thorough understanding of an area of interest, whether it be space policy, new innovations, mission requirements, etc., and the implications of this area to the development of the commercial space industry. Students were also encouraged to reach out to subject matter experts in their areas of research who had participated as guest lecturers throughout the semester, both as a means of gaining additional insight into their research topics and as a way to continue to strengthen ties between academia and industry. Students then had the opportunity to practice their communication skills by presenting their research to the rest of the class.

In addition to the discussions and research projects, students were required to complete four lab assignments. While on the surface these labs provided an introduction to Analytical Graphic, Inc.'s Satellite Toolkit (STK) and Orbit Determination Toolkit (ODTK) software, their real purpose was to help the students to begin thinking in terms of operational requirements and capabilities. Labs had clear applicability to real-life scenarios and, in some cases, were designed in response to current events. For example, following the failure of Russia's Proton upper stage to place its cargo, the Express-AM4 telecommunications satellite, into its proper orbit in August of 2011, students were given the assignment of re-purposing the satellite and designing a new orbit, given a limited amount of excess fuel and the capabilities available on a telecommunications satellite. With open-ended problems and operational limitations such as these, students are encouraged to step into the minds of satellite operators and develop practical solutions.

The goal of teaching students about practical mission operations will be expanded upon through the lab portion of the course beginning in the spring of 2013. A variety of software currently in use throughout industry has been donated for use in the mission operations center being designed for the course. During the lab component, students will be presented with a sequence of scenarios encountered throughout the operational lifetime of a satellite, including design, launch, and on-orbit operations. However, unlike standard classroom assignments, which tend to present students with idealized situations, a variety of obstacles will be intentionally included in the lab assignments, such as budget overruns, schedule delays, and unattainable requirements. In this way, students will face problems frequently seen in real-world operations and will need to engage in critical thinking and decision-making, justifying their actions along the way.

V. STUDENT PARTICIPATION & FEEDBACK

With the first offering of the lecture-based portion of the course complete, the course's success was evaluated through both the impressions of those involved in the development of the curriculum and student feedback collected throughout the semester. With these insights, potential areas for improvement in subsequent offerings of the course were noted, and some of these changes were in fact incorporated prior to the fall 2012 semester. It is also possible to derive information about what aspects of the course were particularly valuable and thus inform subsequent curriculum efforts.

The first alteration that was made to the course was to internalize a slightly larger portion of the

lectures. With so many guest lecturers involved in instruction throughout the semester, there proved to be a wide variation in the level at which subjects were covered and some discontinuity in the topics themselves. This sentiment was, in fact, reflected in comments through feedback from students. While a large amount of industry involvement is to be desired, providing more guidance concerning lecture content to the guest speakers and delivering some of the key conceptual lectures internally should serve to improve the overall course flow.

A particularly successful piece of the course was the online discussion boards, which developed into several ongoing and vibrant conversations among students throughout the semester. Though only required to make a single contribution each week, most students regularly went above and beyond this minimum, posting both to the current week's topics and continuing to follow and reply to conversations from earlier in the semester. Further, the majority of the contributions were well-thought-out and well-researched, with a great number of insightful links and citations included. Students also used the discussion boards as a jumping off point for their research assignments and final project, either looking further into questions not fully resolved on the boards or simply choosing a topic that came up in discussion and sparked their interest.

The students were very thorough in their research assignments, too, both for the series of mini-research assignments and for the final project. Submissions covered a wide range of subject matter, including topics introduced in lectures as well as those stemming more from personal areas of interest. The majority of students proved to be adept at reducing large amounts of valuable information into concise and informative presentations.

The STK and ODTK labs were met with a slightly more mixed response by the students. A frequent concern arising in the student feedback was that the labs were particularly challenging for students without much background in orbital dynamics, causing them to spend too much time reviewing the physics involved and sorting through the intricacies of the programs rather than focusing on the broader concepts intended to be conveyed through the assignment. On the other hand, there were many students who did enjoy the lab assignments, particularly the Express-AM4 lab and the out-of-the-box thinking it required. On the other extreme, a couple students commented that the labs were too simple, as parts of them were laid out as a step-by-step list of instruction (this was intentionally done to ease the learning curve of the program for those students not familiar with STK).

Overall, despite the struggles faced by some in learning the programs, all were able to successfully complete the labs. The analyses in the students' lab reports showed that the majority of them had a firm grasp of the concepts involved in each lab scenario.

Students were specifically surveyed several times throughout the course to ensure content and topics were appropriately challenging and engaging. When queried about the perceived usefulness of the course content overall, 96% of students found the content to be very or somewhat useful as shown in Figure 1.

Course Content Overall

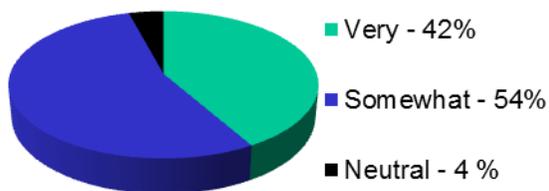


Figure 1. Responses from Students Regarding Perceived Usefulness of the Course Content Overall.

Lectures

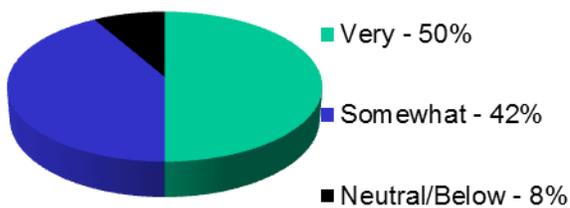


Figure 2. Responses from Students Regarding Perceived Usefulness of the Industry Guest Lectures.

Comparison

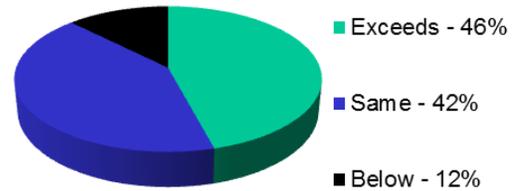


Figure 3. Responses from Students Regarding Perceived Usefulness of the Course when Compared to Other Graduate Courses Taken.

When asked particularly to evaluate the guest lectures delivered by industry, 92% of students found them to be either somewhat or very useful on the whole as shown in Figure 2. Finally when asked to compare this course to other graduate level courses they have or were taking, 46% found the commercial spaceflight operations course to be more useful. When asked, 42% found this course to be of equal value and only 12% thought it to be below the value of other courses. Such comparison was informative mainly due to the diverse backgrounds of the students enrolled in this course. Such diversity manifested as a variety of interests and expertise. This diversity of interest and background appears to have been broadly engaged through the application focused nature of the commercial spaceflight operations course.

Specific feedback from students is listed below:

"I really enjoy this course. It is information that every aerospace engineer should know"

"It is extremely valuable to gain insight from professionals, as opposed to the usually somewhat-limited academic presentation of material"

"I am finishing my Master's degree this semester and a lot of this information is useful to me in understanding how the industry works"

"I like the variety of topics that are covered"

"This course has really stood out to me so far in how everything is very investigative."

These are listed here with the intent of demonstrating the value that students derive from an application focused class. Within the attributes that students identified as most useful there is significant overlap with what industry feedback identified as important. Thus from this limited data, it would suggest that application focused course content is a

valuable addition to a highly technical and focused advanced degree program for aerospace engineering.

VI. NEXT STEPS

While this paper primarily details information and experience gained from the first offering of the lecture portion of the curriculum, concurrent to its presentation, the course is being offered again for a second semester. This second offering has 20 students currently enrolled, bringing the combined reach of both semesters to 48. Simultaneously, efforts are ongoing in the process of developing the second semester portion of the curriculum which consists of a simulated operations facility for students to gain firsthand experience performing simulated operations. The current status of this development is progressing well. Construction for the lab itself is ongoing, and dialogue with industry partners regarding operational software and scenario generation are progressing on schedule. Below is a conceptual rendering of the lab, which will be able to hold at least 24 students and will also have the capability of including distance education students or remotely collaborating teams.



Figure 4. Impression of mock Mission Control Center currently under construction.

Following the establishment of the lab section of the course, the intent of the project is to codify the curriculum in a Graduate Certificate in Spaceflight Operations. Such a certificate will require other critical pre-requisite classes as well as the two-course sequence outlined here. Additional effort will be focused on leveraging the lessons learned and the content generated for more repeatable and widespread implementation at other institutions of higher education. The format of this dissemination is under consideration with the intent of making the key attributes available to interested institutions to utilize in the most efficient manner possible.

VII. CONCLUSION

The University of Colorado at Boulder, in partnership with the FAA's Center of Excellence for Commercial Space Transportation, is currently in the process of developing graduate level curriculum to

train students in the area of commercial spaceflight operations. The curriculum will serve to satisfy three main goals, that of serving as a bridge between academic theory and commercial applications, fostering and facilitating collaboration between academia and the commercial space industry, and providing a venue for dialogue and research encouraging operational improvements in the space industry. The university setting is ideal for achieving these goals, as it contains a highly educated graduate student body with the requisite technical and theoretical background and offers a low-risk environment for new research.

Development of the curriculum involved extensive industry involvement, both for the lecture-based and lab-based portions of the course. Industry participated as guest lecturers, provided the feedback needed to ensure that course content remained relevant to today's commercial environment, and donated the software and development efforts needed to organize lifetime operations lab procedures practical for the constraints imposed by the academic school year.

The lecture portion of the course was delivered for the first time in the fall 2011 semester, with a great deal of success. Students were particularly engaged in the online discussions and completed very thorough presentations for each of their research assignments. While the lab assignments were faced with slightly more difficulty by a few of the students, the majority of the class was eventually able to successfully complete the assignments and take away the important operational aspects being conveyed through the labs.

Efforts are ongoing in the development of the mission operations center that will be used for the lab-based, second semester of the curriculum. The lab space itself has been established, with procurement of both hardware and software both currently taking place. The operations center will be ready for the first offering of the lab course in spring 2013.

Although the FAA has sponsored this project, it neither endorses nor rejects the findings of this research. The presentation of this information is in the interest of invoking technical community comment on the results and conclusions of the research.

APPENDIX I – INDUSTRY AND GOVERNMENT PARTNERS (ALPHABETICAL ORDER)

Altius Space Machines
Analytical Graphics Incorporated (AGI)
Arianespace
Bigelow Aerospace
Clear Channel Satellite
Digital Globe
GeoEye
Jet Propulsion Laboratory (JPL)
Lab for Atmospheric and Space Physics (LASP)
Lockheed Martin
NASA
Orbital Sciences Corporation
Sierra Nevada Corporation Space Systems
Space Exploration Technologies (SpaceX)
Special Aerospace Serviced (SAS)
The Space Foundation
United Launch Alliance (ULA)
United States Air Force
Virgin Galactic

APPENDIX II – ACADEMIC OBJECTIVES

“The Commercial Spaceflight Operations course shall serve as a bridge between theory and application to prepare real world problem solvers.”

With extensive input by industry and government partners, this overall course objective led to the following academic objectives:

1. Comprehension of mission lifetime
 - Mission planning through end-of-life
2. Understanding of constraints
 - Technical: What can you do
 - Policy/Legal: What are you allowed to do
 - Business: What can you afford to do
 - Practical: How do you adapt
3. Insight into and understanding of industry practices
 - Current industry practices
 - Potential improvements

4. Overview of project management and team dynamics
5. Understanding of risk
 - Risk vs. cost
 - Quantification of risk

APPENDIX III – COURSE TOPICS

1. Background
 - Course Introduction
 - Industry and Government Introduction
 - Industry and Government Challenges
2. Launch
 - Launch Overview: Technical Review
 - Launch Vehicle Overview
 - Launch Constraints
 - Human Launch Considerations
 - Sub-Orbital Flight
3. On-Orbit
 - Attitude/Rendezvous and Docking
 - Operations Overview
 - Safety and Mission Assurance
 - Spacecraft Subsystems
 - Industry Overview
 - Payloads
 - Human Factors
 - Orbit Determination
 - Conjunction/Debris
 - Ground Station Operations/Design
4. End-of-Mission
 - Re-Entry Overview
 - End-of-Mission Options
 - Quality Sciences/Cost-Plus vs. Commercial Contracting
5. Mission Planning
 - Mission Design
 - Construction/Integration Overview
 - Mission Assurance, Contingency Plan, and Risk Reduction
 - Financial/Contracting Overview
6. Miscellaneous Topics
 - On-Orbit Fuel Depots/Satellite Servicing
7. Conclusions
 - Summary/Current Issues
 - Space Policy Overview
 - Individual Research Projects