Bringing Together Industry and Academia via Graduate Commercial Spaceflight Operations Curriculum

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A graduate level curriculum covering topics in commercial spaceflight operations has been developed at the University of Colorado at Boulder. This paper outlines the high level insights gained through this process with the explicit objective of enabling dissemination to other institutions of higher education. Furthermore, several synergistic areas in the domains of technology, business, and operations have been identified that are benefiting from collaboration between industry and academia. Continued efforts in these areas are expected to produce innovation and improved technological solutions for the space industry.

Nomenclature

COE	=	Center of Excellence
CSO	=	Commercial Spaceflight Operations
CCAR	=	Colorado Center for Astrodynamics Research
CST	=	Commercial Space Transportation
CU	=	University of Colorado

I. Introduction

SPACEFLIGHT operations is a technical area that has been evolving since the 1960s and is continuing to change today. Commercial space is a sector of the overall space industry which arguably started shortly after world superpowers blazed the trail into space. This sector and variations on its title have received renewed interest as of late, with technical and business pioneers pushing to expand the reach of commercial spaceflight activities to include human flights to sub-orbit, orbit, and beyond. This paper explores the development of a graduate level curriculum covering Commercial Spaceflight Operations at the University of Colorado at Boulder. This curriculum was created, and is constantly evolving, to provide an academic environment within which education and collaboration can be fostered.

For the purposes of this curriculum, commercial space is broadly defined to include communication satellites, manufacturers, launch vehicles, service providers, and others who operate based on commercial principles in the space sector. A useful working definition of commercial space can be found in the 2010 United States Space Policy where it is defined as:

> "space goods, services, or activities provided by private sector enterprises that bear a reasonable portion of the investment risk and responsibility for the activity, operate in accordance with typical market-based incentives for controlling cost and optimizing return on investment, and have the legal capacity to offer these goods or services to existing or potential nongovernmental customers."

Leveraging this definition to establish the scope, this paper will outline the processes, procedures, and lessons learned throughout the process of establishing a graduate level curriculum in Commercial Spaceflight Operations. The ultimate objective of this documentation and referenced material is to enable the dissemination of such curriculum to other institutions.

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The focus of the curriculum is commercial activities; however, it would be naive to ignore the extensive experience and body of knowledge generated by government space activities. While some commercial activities seek to specifically streamline operations to avoid pitfalls of government spaceflight operations, the combined activities from governments across the globe in both military and civil space are crucial components of this curriculum. In many cases, this interaction with government entities is obvious, as is the case when government entities serve as the regulator of spaceflight operations or when they serve as direct customers to commercial providers. Going further, there is much experience in the realm of operations resident within government institutions, and this resource is considered intricately relevant to commercial spaceflight operations.

While fusing experiences and information from commercial and government sources provides an extensive background for a curriculum, the efforts described in this paper are further enhanced by including relevant academic experience and research. Bringing together commercial, government, and academic perspectives and strengths allows for a well-rounded comprehension of spaceflight operations and provides a capable platform to research and understand relevant issues and constraints spanning all spaceflight operations.

Broadly speaking, the objectives of the Commercial Spaceflight Operations curriculum development effort are to educate students and facilitate collaboration between academic, governmental, and commercial entities.

II. Background

The Commercial Spaceflight Operations curriculum discussed in this paper was developed at the University of Colorado at Boulder in the Aerospace Engineering Sciences Department and the Colorado Center for Astrodynamics Research. The research efforts associated with this CSO curriculum were supported by the Center of Excellence for Commercial Space Transportation (COE CST), which is a program initiated and funded by the Office of Space Transportation (AST) within the Federal Aviation Administration (FAA).

The initial efforts associated with this research activity focused on the development of a prototype curriculum, as outlined later in this paper. This curriculum, developed and informed from extensive research, was then offered as two sequential classes at CU Boulder. These course offerings served to inform further refinement of the curriculum components and topics. It should be noted, however, that the research effort and the course offerings are distinctly different activities. The combination of these two activities would not have been possible without the support of both the FAA AST and the Aerospace Engineering Sciences Department leadership at CU Boulder.

By way of context, the curriculum consists of two courses. The first is lecture-based and primarily exists to introduce topics and provide context on commercial spaceflight operations. The second is lab-based and provides operational experience and context. The lecture course was first offered during the fall semester of 2011, and a paper was presented based on the experiences of creating this initial course offering at the 2012 International Astronautical Congress[1]. The lecture portion of the curriculum has been offered a total of three times, and the lab portion is currently finishing its second offering. In total, through these five semesters, the curriculum has reached 81 students. Although the curriculum is intended to be a two-semester sequence, the lecture course has thus far seen higher participation than the lab.

III. Curriculum Approach/Lessons Learned

In an effort to document the process through which the CSO curriculum at CU Boulder has been developed and is continuing to evolve, this section will provide an overview of what has been done and the resulting lessons learned. Documentation of these activities is intended to provide insight to curriculum developers from other programs and is also intended to solicit continued feedback from industry and government experts in the domain of spaceflight operations. It is important to note that this curriculum has relied heavily on industry insight throughout its development and refinement. It is also valuable to acknowledge that there have been many changes to the curriculum and there are many further changes expected.

A. Development Process

The development process for this curriculum was extensive and methodical. The content covered in the curriculum must continually evolve due to the immense body of knowledge that exists as well as ongoing innovations in the sector. For this reason, extensive work was done prior to the first lecture. This work continues today and is expected to be a requisite attribute of the curriculum going forward. Unlike some disciplines that have well defined textbooks and easily defined scope, the field of commercial spaceflight operations is continuously changing and evolving. Thus, in addition to constant revisions and evolution, the development and successful execution of this curriculum requires continued exposure to industry and government activities and trends. This is primarily accomplished through review of relevant industry publications and attendance at industry events, conferences, and symposia. The process of this development work will be outlined in this sub-section, with further details of each component of the curriculum contained in subsequent sub-sections.

The genesis of this curriculum can be traced to discussions with members of the commercial space industry regarding the need for graduates to understand the context of the technical designs and decisions they make directly out of school. Several such conversations preceded the establishment of the COE CST by the FAA. Upon its establishment, the task of developing such a curriculum was proposed and selected as a task within the Center of Excellence.

Once accepted as a task within the Center of Excellence, the originally proposed effort was further expanded, resulting in the creation of a draft set of academic objectives and key topic areas to be covered. This original draft of the course's academic objectives was distributed to a broad spectrum of industry and government experts in all major areas of spaceflight operations. The group of over two dozen industry and government members that responded provided varying levels of input. An overview of some of this input is included in the next sub-section. Of the original group of industry and government contributors, many provided follow-up input as the curriculum developed and participated as guest lecturers at CU. Additional industry and government representatives provided input and feedback at later dates.

The academic objectives were refined using the feedback provided, and the resulting objectives and key topics were presented and reviewed at the 17th Improving Space Operations Workshop in Boulder, CO on April 5-6, 2011. Incorporating the immediate and follow-on feedback from this event, the objectives were further fine-tuned to the point where a detailed course outline could be generated. This detailed course outline allowed for specific follow-up and contact to be made with subject matter experts in the areas identified as key components of the curriculum. The subject matter experts provided valuable input on what specifics should be covered and to what detail. A representative distribution of these experts was subsequently invited to provide guest lectures during the first offering of the curriculum during the 2011 fall semester.

Several times throughout the first semester in which the curriculum was offered, students enrolled in the class were polled to identify expectations, likes, dislikes, and suggestions. Similarly, guest lecturers provided feedback and contributed valuable content on the state-of-the-art for spaceflight operations. In many cases, this content was the starting point for further extrapolation for future lectures. Many of these reviews served as the basis for changes to parts of the curriculum when offered in subsequent years.

During the months following this first course offering, significant refinement was done on the original curriculum and on the infrastructure and design for a follow-on lab section. The details of this development are discussed below.

Fall 2012 saw the second offering of the lecture course, during which time extensive guest lectures were again included in the semester. Many of these guest lectures covered different but complimentary topics relative to the guest speakers from the first semester. This provided varying content and perspectives to the development process. Just as with the first offering of the lecture course, ongoing feedback was solicited from both students and guest speakers.

Building on the lessons learned through student and industry feedback throughout the entire curriculum development and course offering process, the lab portion of the curriculum was first offered during the spring of 2013. This required extensive infrastructure renovations and industry collaboration, which will be further reviewed in upcoming sub-sections. Following this successful first offering of the lab, another cycle of courses was initiated in the fall of 2013, and the lab was offered for a second time during the spring of 2014. This second offering included extensive changes and modifications.

The current status of the curriculum development is focused on the dissemination of lessons learned and on the establishment of a Graduate Certificate within the Master of Science program at CU Boulder. Along with the creation of a new Graduate Certificate, specific emphasis is being placed on securing longevity and sustainability for the curriculum by documenting key topic areas and expanding involvement from other faculty and staff at CU Boulder and beyond.

B. Industry Input

As noted in the previous sub-section, input from industry and government was weighted heavily in the identification of academic objectives and curriculum content. This section will overview some of the high level components of the feedback which drove the curriculum. Extensive opinion was provided on very detailed components of the academic objectives and individual lectures. Appendix A contains the academic objectives, reflecting this input. The curriculum is continuing to evolve based on additional critiques to improve the breadth of input and insight considered.

Several industry and government members who provided feedback specifically inquired about or noted the importance of context for this type of curriculum. Notably, this input strongly pointed to this curriculum being reserved for the graduate level and, in some cases more importantly, that it be a component of a broader and more rigorous technical program. Of those who opined on the topic, there was a broad consensus that this type of contextual content was most beneficial for students working on an advanced degree in a related field. It was the opinion of many who were consulted that highly specific operations relating to individual systems were something that companies taught their own employees and thus were not expected to add much value to a broad graduate level course. Several reviewers also noted that they would expect this curriculum to inform spacecraft and system designers, but that students completing this program would likely not be spending their time explicitly sitting on consoles for operations. This feedback was inherently addressed through the extensive graduate level course offerings within the Department of Aerospace Engineering Sciences at CU Boulder. Furthermore, students enrolled at CU Boulder in programs such as Mechanical Engineering and Interdisciplinary Telecommunications have successfully completed the course.

Another common piece of feedback was the perceived value of covering technical, business, legal, and policy topics in an integrated way. This was somewhat unexpected, but over the several semesters the course has been offered, such convergence of subject matter domains has repeatedly occurred in student projects and guest lectures. This frequent recurrence of cross-discipline topics is seen as a validation of the broad inclusion of such topics. Generally, students in this curriculum are expected to already have a working knowledge of the technical fundamentals required for spaceflight, thus the courses are able to focus on introducing concepts from business, legal, and policy domains that are unlikely to be covered in other graduate level engineering courses. By covering these different aspects of spaceflight operations, students are able to explore applicable problems and constraints faced within the commercial spaceflight industry while proposing actionable and realistic solutions.

A more specific piece of feedback that was received during this review process was the importance of distinguishing between spaceflight operations that included crewed vehicles and those that did not. This distinction may seem obvious, but by specifically calling out the differences, any ambiguity is removed from the curriculum about what requirements are introduced when crewed spacecraft were considered.

Reviewers frequently cited the importance of systems engineering and, more broadly, the value of understanding context within spaceflight operations. This feedback led the curriculum to make a specific effort to provide the systems level context of topics being discussed and resulted in specific guest lectures. These guest lectures included discussion of systems engineering, industry best practices, and statistical quality and process controls. The very nature of the curriculum's broad scope was also noted by reviews. This scope necessitated a focus on context over detail in many instances at the course level. That being said, where the course sometimes required a high level focus or a specific deep dive example, students were able to delve into topics relating to their specific interests through both tailored and open-ended assignments. These assignments will be briefly discussed in the following sub-section.

An overview of the industry and government organizations that have been involved with this curriculum at various stages is provided as Appendix B.

C. Lecture Development

The lecture course of the CSO curriculum is the most refined, having been offered three times prior to the publication of this paper. This section will provide information about the lecture course, including key components and changes that have been made based on feedback and experience. The lecture course itself can be broken down into several core components: lectures, assignments, discussions, labs and final projects. The lectures and associated content drives much of the subsequent exchange of ideas. Assignments are open-ended in nature and allow students to explore topics or areas of particular interest. Further, all students enrolled in the course are required to engage in discussions about current events, lecture content, or other items of interest relevant to commercial spaceflight operations. Students are also assigned four lab assignments, which have evolved since the first offering of the class but generally provide a more structured and in-depth exploration of relevant topic areas. The culmination of the semester is contained in the final project, which comprises a significant portion of the students' course grade and includes a project proposal, a final presentation, and a final paper. The topics for these final projects are focused on identifying constraints or problems within commercial spaceflight operations, detailing the history and context of this problem, proposing solutions to the constraint or problem, and evaluating the proposal using various technical and non-technical tools, techniques, and methods.

Before diving into the details of each of these core components, the importance that distance learning has played in the development and execution of this curriculum should be addressed. The curriculum has been able to benefit significantly from the distance learning capabilities established within the School of Engineering and Applied Sciences at CU Boulder. These capabilities include fully wired studios for instructing classes that are outfitted with state-of-the-art projection hardware, full audio and video recording of lectures, and remote presentation functionality. The distance learning studios are staffed with technicians who have made many valuable features of the CSO curriculum possible. The most obvious benefit has been the inclusion of students from across the country that have been able to enroll in and complete the lecture course. In many cases, these distance students are working for commercial space companies, related firms, or government spaceflight entities. Of the 74 students who have completed the lecture course over the past three semesters, more than 1/3 (27) have taken the class remotely. Additional benefits that this distance learning capability has afforded the curriculum are the ability to record lectures and enable remote lecturers. In terms of recording lectures, this functionality has allowed for guest lecture content to be reviewed in preparation of developing future lectures and has allowed students in subsequent semesters to view guest lectures from earlier semesters. The functionality that allows for recording lectures also permits lectures to be given remotely. This capability has been leveraged for specific guest lecturers who were unable to travel to Boulder to give a lecture in person and also, more recently, was used to deliver a significant portion of the lecture course that covered telecommunications. This feature was enabled through the connected projection capabilities, audio and video capture devices in the lecture studio, and the use of GoToMeeting software.

The lectures themselves are scheduled twice a week from 5-6:15 local time. This schedule allows for fewer but more in-depth lectures. The timing, coming at the end of the day, has facilitated the participation of industry and government guest lecturers, as well as distance learning students who work during the day. The first two semesters of the lecture course were comprised predominantly of guest lectures. This was a strategic decision in order to provide extensive insight on important content and challenges within the spaceflight industry. These lectures were intended to be scheduled such that a logical flow of lecture content was maintained throughout each semester. The challenge of scheduling speakers, however, resulted in somewhat scattered subject matter. To address this reality, the third offering of the lecture course had a slightly different structure, as follows.

The first third of the semester was primarily lectures given by the course instructor based partly on the two prior semesters of guest lecture content and feedback. Furthermore, an interdisciplinary component was added experimentally, based on insights from previous teachings of the course. Bridging departments and disciplines, the third offering of the course was taught in conjunction with the Interdisciplinary Telecommunications Program at CU Boulder, which traditionally offers a satellite communications course. This interdisciplinary aspect provided a more diverse student base, spanning both telecommunications and aerospace engineering, and also allowed for in-depth instruction on telecommunications components related to commercial spaceflight operations. The interdisciplinary nature of the course is expected to continue in future offerings of the course; however, some changes are expected in response to student feedback. Finally, the remaining third of the semester was reserved for guest lectures. With a couple of exceptions for lecturers who could only attend earlier in the semester, this structure provided ample context to students from background lectures and thus enabled more extensive dialogue with the guests. The more structured approach, with strategic scheduling of guest lectures, is a change in the curriculum that is expected to take hold based on the positive responses of both students and guest lecturers.

In all three semesters, the schedule of topics covered during lectures was designed to reflect the timeline of a spaceflight mission. Each semester began with several lectures covering the background and context of commercial spaceflight operations, including legal and policy considerations. Lectures then turned to topics relevant to a mission lifecycle. This lifecycle sequentially spans mission design and planning, manufacturing considerations, launch vehicles, orbital transfers, mission operations, and end-of-mission considerations. A commercial communications satellite was typically used as a case study throughout each of these phases due to the high frequency of such missions in industry and the resulting availability of information. That being said, the lecture also covers commercial human spaceflight and extensively explores more ambitious case studies for commercial spaceflight through invited guest lectures.

The second core component of the lecture portion of the CSO curriculum is the individual student assignments. These assignments have remained relatively constant since the inception of the lecture course. The assignments task the students to select a specific topic of their choosing from within the scope of the course and perform additional research on that topic. This research is expected to cover, to the maximum extent possible, published academic research and technical reports, as well as popular press articles and press releases. In many cutting edge topic areas, there is limited peer reviewed or formally published technical information and often students were required to creatively find context and other references that would support or dispute statements and claims made in more informal sources. The students are tasked with presenting the information they find during this independent review as a short and concise five slide presentation. The students are then periodically asked to present this material to their fellow students at the beginning of lectures. Throughout the semester, students are required to complete four of these independent assignments and are free to either continue researching the same topic or change topics between assignments. Many students take advantage of this flexibility to better understand topics that they are considering for their final projects, which will be discussed later in this sub-section.

The third core component of the lecture course is student participation – primarily in the form of on-line discussion boards, although students are expected to attend all classes, participate in in-class discussions, and engage in question and answer opportunities with industry guest lecturers as well. Traditionally this would be sufficient for earning a participation grade in a class, however the inclusion of distance learning students for this course present a unique challenge of equity and participation value. For this reason student participation is primarily evaluated through their substantive contributions to an online discussion board. Students are graded weekly on their contributions and these grades are based on the extent to which students bring in outside information, references, and/or career experiences to the topics being discussed. Generally there are a variety of topics covered, including both current events and topics brought up in lectures. While many students may not have experienced this aspect of participation prior to the course, most find it incredibly useful throughout the semester. Students particularly find it beneficial to hear from other students who come from different academic backgrounds or who are currently employed in the industry and can thus provide invaluable personal insight. Previous distance students who have taken this course include employees of a commercial launch vehicle company, a NASA employee tasked with managing exciting space station operations, multiple members of the military directly involved with space operations and space situational awareness, and faculty members from other institutions. While there are drawbacks to the types of virtual discussions included in the course, the pros seem to outweigh the cons, and the discussion boards are expected to remain a core component of the class in future offerings.

Lab assignments comprise the fourth core component of the course. The requirements for the lab assignments are more in-depth than the individual assignments discussed earlier and in some cases allow collaboration among students. In the first offering of the course, these labs were exclusively technical in nature and leveraged industry software to provide hands-on technical challenges to students. Based on student feedback, the second offering of the course reduced the number of technical labs in exchange for the introduction of a business strategy lab. Continuing this trend in the most recent offering of the course, the first lab focused on astrodynamics, the second lab focused on covering the core components of a business model in the space industry, the third lab covered technical aspects of telecommunications from space, and the fourth lab focused on the identification of key factors in strategic business planning. This mix of technical and non-technical seems to be the sweet spot for the course moving forward based on student feedback. One particular challenge was finding the appropriate balance of technical background required for astrodynamics and telecommunications when the course became interdisciplinary. In most cases, students were able to individually perform the required background work to complete the assignments. This flexibility reinforced the value of offering this course at a graduate level and within the context of other technically challenging courses.

The fifth and final core component of the lecture course is a final project. This project is assigned as an individual activity and is worth a substantial portion of the students' grade for the course. Students are tasked with identifying a constraint or problem faced during commercial spaceflight operations and are required to provide background and context of their selected topic, proposed solutions, and an evaluation of these solutions using technical and non-technical analyses. The deliverables are a project proposal, which is due mid-semester and allows for instructor input and feedback; a presentation to be given to the rest of the class; and a final paper overviewing the analysis and information collected. Distance students are held to the same requirements and must present their projects either via video conference or audio recording. Many students use their assignments completed throughout the semester as a foundation for this project. A primary intent of this final project is to enable a critical review of spaceflight operations that may not be possible within industry and government entities for various reasons. Leveraging the ability to question historical procedures and propose what amounts to radical departures from heritage is a valuable opportunity that academia affords to students. In several cases, this freedom has resulted in proposals for revolutionary business ideas, fundamental changes to government policy, modernization of spaceflight operations procedures, and much more. A selected subset of these topics include: a new architecture for government space situational awareness services, orbital fuel depots, commercial space suits, commercial orbital demand, integration of space traffic and air traffic, laser communications, asteroid mining, commercial human missions beyond Earth orbit, automation, launch vehicle development and re-usability, and electric propulsion. In many cases, these final projects leverage industry insight either from guest lecturers who have volunteered to support the project remotely or from personal experiences of students who may have worked on certain problems in their careers.

D. Lab Development

In addition to the overall academic objectives of the CSO curriculum, the lab course was designed around infrastructure built using investments from the School of Engineering and Applied Sciences, the Department of Aerospace Engineering Sciences, and the Engineering Excellence Fund at CU Boulder. The guiding objectives of this lab development were to: push the state-of-the-art for education, extensively involve industry, apply theories to real-world challenges, provide infrastructure to expand research activities, enable other courses to be taught or improved, and exhibit existing and on-going research.

To achieve these objectives a former research lab was completely renovated from what used to be a wet lab into a fully outfitted operations lab capable of simulating aspects of spaceflight missions while simultaneously enabling advanced research. The process by which this renovation was accomplished has several key lessons learned that are worth sharing for others that might attempt similar activities, as outlined below. Figure 1 shows the initial computer aided layout for the lab and Figure 2 shows several pictures of the completed lab.

Figure 1. Pre-Renovation Computer Layout Design. *This shows the overall concept of the lab given the space available.*

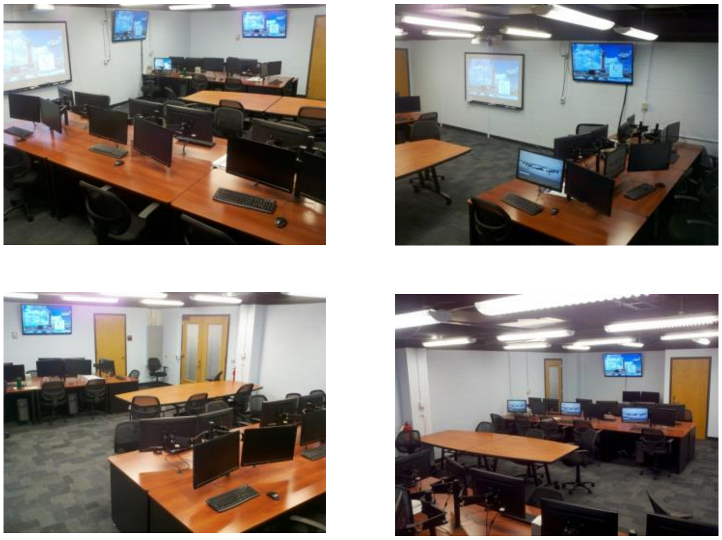

Figure 2. Post-Renovation Commercial Spaceflight Operations Lab.

A key attribute of the lab is the multiple screens available for projecting information. This lab uses three televisions and a smart-board projector. Displaying the same content on all of these screens simultaneously was a particular challenge. Furthermore, the ability to show student work stations on the displays was highly desirable to enable more hands-on instruction and real time collaboration between students. This would traditionally require routing video feeds through a switch-box, which was prohibitively expensive. After experimenting with several possible solutions, the final set-up accomplishes all of the stated goals at a very low price. The solution is based on a single computer with two video cards. These two video cards combined with a powered HDMI splitter enable the computer to display on all four major screens as well as a local screen at the computer. A software solution is used to display the video feeds coming from both video cards on all screens in the lab. This software solution is a program called Actual Multiple Monitors and enables the cloning of one desktop onto the others. In order to add the functionality of displaying any individual work station in the room on any of the displays, a software solution called Real VNC is used. This allows the display computer to show any screen in the room.

The functionality that enabled video from any work station to be displayed was further enabled by the set-up of the individual work stations. There are a total of twelve computer work stations, which at full capacity are designed to each host two students. This set-up allows for a total of 24 students to participate at lab workstations. These twelve stations are set-up with a highly capable system running Linux. This environment was found to be optimal from a network management perspective. Alternative options for this set-up proposed by industry partners would have resulted in twelve access points of limited independent computational capabilities, which would then access more powerful central server running simulated flight operations software. Although this solution may have been of marginally lower cost, the prerogative to enable research led to a decision that each station would be of sufficient computational capability to process extensive code and data loads. To provide an environment for Windows based programs in the lab, each computer is also equipped with VMWare, software that enables virtual instances of Windows to be created and thus allows for the execution of Windows based software to be used in the lab.

Having defined the infrastructure components of the lab, it is informative to discuss the software side of the lab. This component of the operations lab was the most excruciating and difficult component and in fact almost precluded the lab entirely. The primary challenge was to find a software suite capable of simulating spacecraft operations with sufficient fidelity to be useful, while simultaneously avoiding any software that was restricted under the International Trafficking and Arms Regulations (ITAR). Using software classified under the ITAR would have prevented any foreign national students from enrolling the courses or using the lab in any fashion. Such a restriction was deemed to be unacceptable in the context of the overall academic objectives of this project. After several dead ends with industry partners, the foundational software enabling this lab was secured without limiting the nationality of students enrolled in the course. The primary tools used by the lab are the ACE Premier™ Flight Dynamics System provided as an industry contribution from Braxton Technologies and the System Tool Kit (STK) provided as an industry contribution from Analytical Graphics Incorporated. In addition to these software tools, students in the lab leverage their own code, Google Earth, and additional tools developed by academic partners in the COE CST for launch trajectory optimization and statistical launch safety calculations.

The lab semester, in its first offering, focused on lectures and student activities to provide operational context and understanding of pre-launch integration, launch, orbit transfer, on-orbit operations, and end-of-life disposal for a geostationary (GEO) communications satellite. This offering of the course was completed with a final group project applying the lessons learned throughout the semester to a mission concept of the students' choosing. The students of the first class chose to evaluate the feasibility of and develop a concept of operations for an asteroid mining mission. Based on feedback from students and industry, the second offering of the lab departed in several significant ways from this model. In its current form, the lab has three major components: lab based scenarios, individual research projects, and a semester long group project. The lab based scenarios focus on the key operational activities of a GEO communications satellite, as they did previously. Individual research projects provide students with an opportunity to explore spaceflight concepts that are of interest to them, which is a new addition to the lab. The major change, however, has been with the introduction of the group project as a semester long activity with extensive industry involvement. The current project is externally supported by SSL, and the students are evaluating the operational constraints and performance of an all-electric transfer from different parking orbits to GEO. This project benefits significantly from weekly meetings between the students and members of the engineering team at SSL. At the time of submission for this publication, the students had completed a mid-term review and are in the final stretches of completing the agreed upon deliverables. This new structure for the lab is expected to continue in the future, as it has been very well received by the students, instructors, and industry partners.

E. Student Feedback

A very important component of the CSO curriculum at CU Boulder is extensive and thorough solicitation and review of student feedback. Unlike the required review mechanism employed by most universities (CU Boulder included) that ask students to provide generic feedback at the culmination of the course, students in the CSO classes are queried multiple times throughout the semester. In general students are asked to provide feedback at the very beginning of the course, allowing the instructors to establish a baseline of expectations and student backgrounds. The students are again queried in the middle of the semester. These reviews have been invaluable to identify challenges or issues with the course in sufficient time to improve items for the second half of the semester and have allowed for tactical pivots in areas such as teaching assistant availability, timeliness of grading, and uncertainty of course expectations. In multiple cases, this mid-

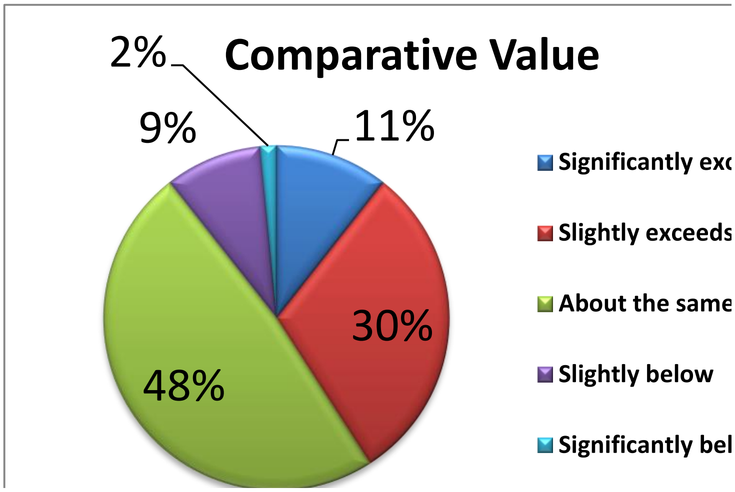

Figure 3. Student feedback on the comparative value of the CSO curriculum compared to other classes they have taken during graduate school.

semester feedback allowed changes to be made that prevented students from becoming disengaged from the course or performing poorly due to components of the class outside of their control. Finally, students are requested to also provide critiques at the end of the semester. This feedback is very specific in most components of the course and allows for improvements to guest lectures, assignments, and other components as needed. Some of this feedback is shown in Figure 3 which represents a question that specifically queried how students viewed the curriculum in the context of other courses that they have taken during graduate school. The intent of this question is to ensure that the CSO curriculum maintains parity in the eyes of students to other courses.

F. On-going Industry Response

In addition to opinions from students, the CSO curriculum places a high value on feedback from industry and government partners. Through specifically solicited feedback, guest lectures, and collaborative industry-student projects there has been numerous opportunities to collect feedback. Some of this input has been specifically discussed in previous sub-sections. A specific demonstration of industry interest in this work, however, is useful to point out. Numerous industry partners have articulated a clear desire to hire students who have completed the curriculum in commercial spaceflight operations. Three students have secured employment positions within the commercial industry as a result of participation in this course. Furthermore, current partners engaged with the lab have made clear a desire to hire, as interns or full time, more students than are currently enrolled in the course. This clear declaration of interest is taken as positive feedback for the curriculum, and continuing to provide this pipeline for industry partners is a key objective of the curriculum moving forward.

IV. Industry and Academic Impacts

The collaboration between industry and academia that has occurred as a result of the commercial spaceflight operations curriculum at CU Boulder has spanned many subject areas, industry sectors, and technical domains. The most straightforward benefit of a curriculum that heavily emphasizes input from industry is the creation of students with perspective and broad understanding of industry trends and realities. Moving beyond this, within the context of a graduate program, a curriculum such as this provides direction and support to students in search of topic areas to allocate extensive research efforts in pursuit of advanced degrees. Traditionally much of this research is directed by partnership with government based funding entities that have unique and challenging problems for graduate students to study in pursuit of M.S. theses and Ph.D. dissertations. The inclusion of industry concerns and feedback to this process can be expected to result in advanced research in areas more closely aligned with industry trends and concerns. This process is not immediate nor is it easily identifiable, however there are many technical areas that have already been identified that would benefit from further studies and the resulting innovations.

During collaboration with industry it was initially expected that information would primarily be going in one direction: from industry to academia. In practice information and benefits have flowed in all directions between government, industry, and academia. Beyond the benefits to general workforce availability and preparation, collaboration has impacted several industry areas of concern or focus, at least partially due to the CSO curriculum at CU Boulder. The following are meant to highlight topics that have seen dialogue, mutual benefit, and further research, these topics are not considered comprehensive or complete.

Automation is a technical area that has seen extensive exchange throughout the curriculum development process. In many cases commercial satellite operators are leading the charge on developing automation for ground segment controls while academia has been developing technologies and approaches that would enable on-board satellite automation. Advances in astrodynamics and optimization have also been at the forefront of many discussions. As academia pushes the state-of-the-art on optimization schemes and exotic astrodynamics solutions, industry has begun realizing that some standard operations and approaches have significant room for improvement. This is exemplified best in the collaborative work currently ongoing with the lab portion of the curriculum and the topic of all-electric orbit raising for GEO communications satellites. Through this partnership, university research in areas of complex system optimization is applied to realistic spacecraft performance characteristics and operational constraints. Similarly, extensive academic research into the space environment is of growing interest to commercial operators looking at non-traditional spacecraft systems such as mid-altitude-Earth orbits, specific orbit raising schemes, and small payloads in low Earth orbit. A final example of this beneficial partnership is in the area of miniaturization and modularity. Universities have led the way in the development of small satellites. While these small satellites are often thought of as educational tools for students to understand the processes of satellite design, construction, and operations, they are increasingly also demonstrating an ability to deliver valuable scientific information. As industry looks to innovate with smaller satellites and quicker design cycles, the lessons learned from academia are becoming more and more relevant within commercial industry circles.

It is interesting to note that in many cases similar problems have been discussed within the context of the guest lectures within the CSO curriculum by different companies in similar and different sectors of the industry. This suggests a latent opportunity for continued engagement by academia with industry to identify and propose solutions to problems that cross companies and sectors within the spaceflight industry. Similarly, emerging sectors of the industry lack significant institutional knowledge. In some cases this is to their benefit as lower cost operations and the avoidance of legacy induced costs make these new players more competitive. In other ways, however, these new sectors and new players are expected to benefit from the body of knowledge that is currently being assembled through the CSO curriculum at CU Boulder and hopefully other schools in the future.

V. Conclusion

Extensive work has been completed at the University of Colorado at Boulder in the development of a graduate level curriculum in Commercial Spaceflight Operations. The primary intent of this paper is to enable the dissemination of this curriculum and its replication at other institutions of learning across the country and around the world. In many cases, specific companies and software have been noted. These references are not intended as advertisements but instead are intended to provide specific annotations to assist other entities in continuing this work while avoiding pitfalls that were encountered by the team at CU Boulder.

Ongoing student and industry feedback has resulted in a curriculum covering Commercial Spaceflight Operations that appears to be meeting the needs and interests of all key stakeholders. This curriculum is constantly evolving and working to better engage partners. Through engagement with industry and government partners, several technical areas of research have been strengthened and improved, and it is expected that such availability of information and knowledge within an academic setting will spur future innovation.

The authors welcome continued feedback on this paper and interest from industry, government, or academic partners. Further information on this curriculum can be found online at ccar.colorado.edu/CSO .

Appendix

A: 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

B: Corporate/Government Partners and Contributors (alphabetical order)

Altius Space Machines
Analytical Graphics Incorporated (AGI)
Arianespace
Ball Aerospace & Technologies Corp.
Bigelow Aerospace
Blue Origin
Braxton Technologies
Clear Channel Satellite
Digital Globe
EchoStar
FAA Office of Commercial Space Transportation
GeoEye
IBM
Intelsat
Jet Propulsion Laboratory (JPL)
Lab for Atmospheric and Space Physics (LASP)
Lockheed Martin
NASA
Orbital Sciences Corporation
SES
Sierra Nevada Corporation Space Systems
Space Exploration Technologies (SpaceX)
Special Aerospace Services (SAS)
SSL
Southwest Research Institute
The Space Foundation
United Launch Alliance (ULA)
United States Air Force
Virgin Galactic

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