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Master of Science in Astronautical Engineering degree at the University of Southern California for the space industry

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ABSTRACT

The Department of Astronautical Engineering at the University of Southern California (USC) focuses on space engineering education. It is a unique space-engineering program in the United States where such studies usually constitute parts of aerospace departments. In addition to full-time on-campus students, its flagship Master of Science in Astronautical Engineering degree program reaches working professionals online through distance education. The growth of this space-focused graduate degree program led to the establishment of a new independent department at USC twenty years ago in 2004. Since its founding, this Department of Astronautical Engineering awarded nearly one thousand Master's degrees to students from across the United States, Canada, and selected locations abroad. The article describes the origin, rationale, focus, structure, coursework, and reach of USC's Master of Science in Astronautical Engineering program. It concludes with the lessons learned in program development which contributed to its success.

1. Introduction

Twenty years ago in June 2004, the University of Southern California (USC) established a new independent academic unit focused on space engineering [1-3]. This development contrasted with the dominating tradition in the academia in the United States to combine aeronautical and astronautical disciplines in aerospace engineering programs [4]. The establishment of a pure-space engineering department culminated the multi-year effort to develop a sustainable independent astronautical engineering program that had begun in the middle of the 1990s [1]. This logical step followed the earlier advocacy in the 1970s and 1980s for a separate curriculum in "pure" astronautics leading to a Bachelor of Science (B.S.) and higher degrees in astronautical engineering [1,2,5,6].

To form the new department, the growing astronautics specialization split from USC's Department of Aerospace and Mechanical Engineering and then expanded and solidified. Within one year, the Department of Astronautical Engineering (ASTE) in the Viterbi School of Engineering (VSOE) introduced the full set of degrees (Bachelor, Bachelor Minor, Master, Engineer, Ph.D., and Graduate Certificate) in astronautical engineering. (The USC School of Engineering was named after Dr. Andrew Viterbi in 2004.) The growth of the new ASTE department and student interest in its programs proved that pure-space-focused engineering academic units could be successful in a highly competitive educational field of more than seventy aerospace-related programs offered by U.S. universities [2].

This article describes the largest educational component of the Department, its flagship degree program Master of Science in Astronautical Engineering (M.S. ASTE). The degree specifically focuses on the workforce development needs of the space industry and government space research and development centers. In addition to traditional, "legacy" space and defense companies, the rapid growth of commercial space brought many new participants and startups pursuing various applications and developing space technology. Serving this expanding sector is among the important goals of the program. The comparison of USC's M.S. ASTE degree with other U.S. and foreign educational programs in space engineering is beyond the scope of this article. The course offerings in space safety and plans for meeting associated educational needs in the future are noted in Section 3.3.

The growth of this USC Master's program led to the establishment of the new department, an event that rarely happens in well-established engineering schools. The M.S. ASTE program combines on-campus students studying full-time and those who work full-time and study part-time through VSOE's Distance Education Network, DEN@Viterbi. Online coursework delivery has become an integral feature of workforce development and continuing education in the U.S. space and defense sectors. Today, online students account for one-half of the earned Master's degrees in astronautical engineering.

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The article first briefly outlines the rationale for establishing the new independent department. Then it describes the M.S. ASTE program structure, admission requirements, coursework, students, instructors, online reach to working professionals and its place in broader aerospace education and workforce development for the global space enterprise. The article concludes by discussing the lessons learned in program development and operations which contributed to its success.

2. Space engineering at USC

Earlier publications [1,2] described the USC Astronautics Program and the rationale for breaking the tradition and forming an independent pure-space-focused engineering academic department. Briefly, the beginning of the space age in the 1950s led to the expansion of the engineering field into new areas of technology and changing the names of many existing aeronautical engineering departments at universities to “aerospace” or some variant of “aeronautics and astronautics” [4]. The curriculum, however, continued to emphasize fluid sciences and engineering and aeronautical applications. Academic departments added some coursework in space-related topics, primarily in orbital mechanics and rocket propulsion, but the space curriculum remained limited in many universities.

At the same time, the U.S. space effort greatly expanded in national security, space science, and space exploration. Today, this growth trend continues, increasingly driven by commercial space. Space technology contributes to the expansion of engineering education, resulting in the establishment of new university departments and programs in the aerospace field. In 2022, the world space enterprise reached nearly $550B annually [7]. The space sector employs now more than 200,000 people in the United States alone [8].

The Accreditation Board for Engineering and Technology [9], ABET, recognized astronautical engineering as separate from aerospace degree in the 1970s. ABET accredits Bachelor of Science (B.S.) degrees in engineering. Engineering Master of Science (M.S.) degrees in American universities do not undergo accreditation. The only exception is Master’s degrees in a couple of military educational institutions as specifically required by law dating back to the early 1950s [1,10].

By the end of 2023, the number of ABET-accredited Bachelor of Science degrees in aerospace-related areas in the United States exceeded 70 [9]. This group includes four B.S. degrees in aeronautical engineering and three in astronautical engineering. The latter three degrees are offered by the U.S. Air Force Academy (the very first accredited B.S. degree in astronautical engineering in 1973), Capitol Technology University (formerly Capitol College), and USC. In addition, ABET also accredited three aerospace-related Master’s degrees in military educational institutions in the United States and 11 Bachelor’s and Master’s degrees in foreign countries [9].

Fig. 1 shows the steadily growing number of accredited new aerospace-related B.S. degrees in the United States through the ups and downs of the aerospace industry since the 1930s. The trend illustrates the response of the educational field to the growth of the aeronautical and then space enterprise.

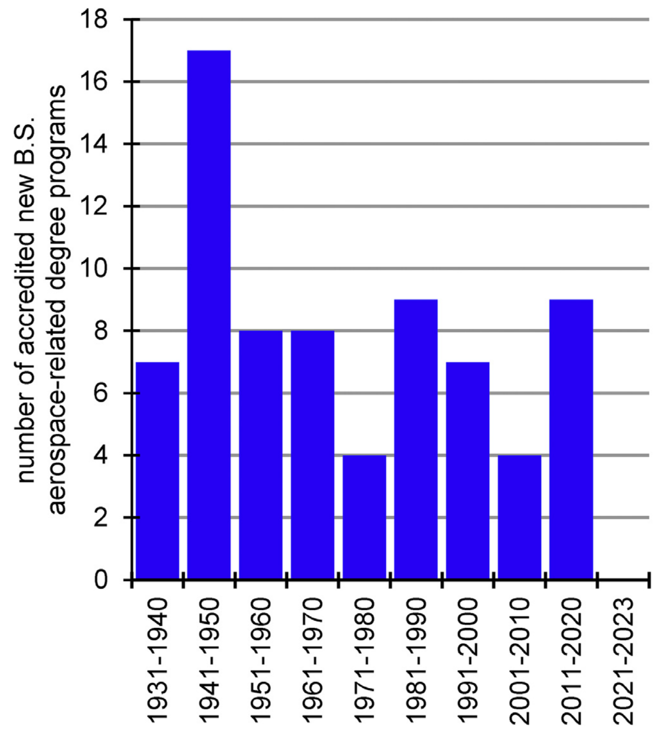

Fig. 1. New Bachelor of Science degrees in the broad area of aerospace, aerospace-related, aeronautical, and astronautical engineering accredited by ABET in the United States during 10-year time intervals. No new programs have been accredited in the early 2020s (2021–2023). Based on ABET data [9].

In the 1990s, aerospace engineering at USC was rather typical for the country. The university is in Los Angeles at the center of a major cluster of space and defense companies and government research and development centers. At that time, most of the faculty of the then Aerospace Engineering Department focused on fluid dynamics research in aeronautical fields since its founding in 1964 [11].

On a historical note, the first man on the moon, astronaut Neil Armstrong, was among the most renowned USC aerospace graduates of the 1960s (Fig. 2). He had studied part-time in the 1950s and early 1960s while stationed as a research pilot at a NASA center at the Edwards Air Force Base in California [2,3,12]. Armstrong then transferred to Houston in Texas after being selected to the second group of NASA astronauts.

After rapid post-World War II growth and large enrollments, aerospace student populations in the United States had dropped by the mid-1990s, following the end of the Cold War [4]. The defiant response of a few astronautics-oriented aerospace faculty at USC to the prevailing doom-and-gloom atmosphere of the 1990s was to found the Astronautics and Space Technology Program (Astronautics Program) [1]. The initiative took advantage of the university’s strategic location at a center of space and defense industries in Los Angeles and concentrated first on the Master of Science degree.

The focus on Master’s students leveraged the capabilities of the Distance Education Network of the Viterbi School of Engineering that initially reached working engineers across the Greater Los Angeles area through televised classes. Advancement of the Internet allowed today’s DEN@Viterbi to transition to webcasting without geographic boundaries [3].

Constrained by the realities of academia, the Astronautics Program built up its coursework relying primarily on part-time instructors, leading specialists working in local companies. Such an approach allowed finding highly qualified lecturers in specialized areas without a lengthy and uncertain process of hiring tenured faculty which would have been very limited in their numbers in any case. In 1996–1997, the faculty formed a new specialization in astronautics within the broader Master’s degree in aerospace engineering. Then, the University followed by approving a new Graduate Certificate with a specialization in astronautics in 1997 and, one year later, the astronautical specialization in the Bachelor of Science degree in aerospace engineering.

In 2004, the University of Southern California split the growing Astronautics Program from the Department of Aerospace and Mechanical Engineering and formed a new independent academic

Fig. 2. Bronze statue of Neil Armstrong on USC campus. Sculptor: Jon Hair. Photograph (2013) by Mike Gruntman.

unit, today's Department of Astronautical Engineering [1-3]. The author of this article served as the founding chairman of the department from 2004 to 2007 and chaired it again from 2016 to 2019. He has also been directing, without interruption, the Master's program since its inception in the middle of the 1990s until this day.

The experience with the growing Astronautics Program led to a call for the establishment, in some universities, of separate pure-space-focused engineering departments to better meet the needs of the space industry and government centers [1]. Such independent astronautical engineering academic units could shift the existing (rarely fair) competition among groups of faculty within aerospace departments to a (much more even-leveled) competition among aerospace, astronautical, and aeronautical departments of various universities.

It was specifically emphasized that creating astronautical engineering departments presented a practical approach to achieving the desired flexibility in the broad aerospace engineering education field under the constraints of realities of the glacially-changing academia burdened with significant inertia and internal politics [1]. The resulting competition among the existing aerospace and aeronautical departments and new astronautical departments of various universities would then naturally force a balanced mix of the offered programs, determined by national and international educational needs, and thus better respond to the engineering workforce development challenges of the global space enterprise.

During the two short decades since its founding, the new space-focused Department of Astronautical Engineering awarded (as of summer 2024) more than 270 Bachelor of Science degrees, nearly one thousand Master of Science degrees, over 50 PhDs, and nearly 20 graduate certificates in astronautical engineering.

On-campus student opportunities include participation in faculty research as well as in student groups such as the Rocket Propulsion Laboratory (RPL) which builds and launches solid-propellant rockets [13] and the Liquid Propulsion Laboratory (LPL) developing liquid-propellant rocket engines [14,15]. In 2019, RPL distinguished itself by becoming the first student group in the world sending a rocket above the Kármán line at the 100 km altitude [16]. LPL has been designing, building, and testing liquid propulsion engines with increasing sophistication [15,17-19], including regeneratively cooled 3D-printed engines using kerosene and liquid oxygen.

The Space Engineering Research Center (SERC) [20], operated jointly by the Department of Astronautical Engineering and VSOE's Information Sciences Institute (ISI), actively involves astronautics students in its programs. The Center emerged from an initiative to create a "Bell Labs of Space" in the early 2000s to advance science and engineering for cost-effective government microsatellite systems which subsequently expanded into other related areas of space technology and specialized workforce development [2]. Later, SERC changed its focus away from the initial objectives toward student-centric space projects [21,22], including cubesats and other programs.

The comparison of USC's M.S. ASTE degree with other U.S. and foreign educational programs in space engineering is beyond the scope of this article. (Some details of these programs are discussed in [2] and references therein.) We only note here that two leading spacefaring nations, the former Soviet Union (the Union of Soviet Socialist Republics, or U.S.S.R.) and the People's Republic of China (PRC), established many pure-space-focused educational institutions graduating numerous space engineers each year. After the end of the Cold War, the Russian Federation and Ukraine (the successor states of the U.S.S.R. with substantial space and rocket capabilities), scaled down these programs. At the same time, the PRC significantly expanded its space activities in national security, scientific, and application domains. Several specialized graduate programs in space engineering also emerged in Europe, South America, and elsewhere in Asia during recent decades.

We focus below on the Master of Science in Astronautical Engineering degree at USC which remains the largest program in the Department of Astronautical Engineering and can be earned by studying on campus or online.

3. Admission requirements and degree coursework

3.1. Admission requirements to master of science in astronautical engineering

The USC M.S. ASTE degree is open to qualified students with Bachelor of Science degrees in engineering, mathematics, and hard sciences from regionally accredited universities. In addition to satisfactory grade point average (GPA) and general record exam (GRE) test scores, applicants also provide two letters of recommendation. During the Covid pandemic, USC suspended the GRE requirements. The restoration of the quantitative GRE metric in applications is essential for preserving the quality of the program and avoiding a slide to harmful social engineering in admissions, with the associated inevitable decline.

In an important distinction from many aerospace programs, applying students do not need to have aerospace-related Bachelor's degrees. The modern space industry and government centers employ engineers of diverse backgrounds who have majored in various areas of science and engineering. Many full-time working engineers strive to continue their education part-time in the space technology field directly relevant to their industry. The M.S. ASTE program opens a path for them to earn a Master's degree in astronautical engineering without prior undergraduate aerospace coursework. Students graduating with non-aerospace Bachelor's degrees can also continue their full-time studies by enrolling in the M.S. ASTE program to prepare for careers in the space enterprise.

The M.S. ASTE degree requires taking an overview course on the fundamentals of space systems (Spacecraft Systems Design). It addresses the challenge of admitting students with non-aerospace backgrounds. The course serves the role of a "rocket-science boot camp." It provides scientific and engineering basics of space systems and rocketry, introduces nomenclature, covers fundamentals of main spacecraft subsystems, and prepares students for specialized coursework in various areas of space technology [23]. The course is also popular among engineering graduate students pursuing degrees in non-space areas but planning to gain employment in the space industry. More than 2400 graduate students have taken this course at USC since 1996 when the author of this article had begun teaching it.

Today, USC's M.S. ASTE students consist of 40% of those with an aerospace-related undergraduate background; 35% with Bachelor's degrees in mechanical engineering; 10% in physics, astronomy, and astrophysics; 5% in electrical engineering; and the remaining 10% spread across all possible flavors of engineering and science. The M.S. ASTE program also occasionally attracts students with non-technical degrees such as medical doctors.

In cases of limited science and engineering educational background, students are asked to take, before applying to the program, typical undergraduate courses in mathematics and physics required in engineering majors. The applicants usually complete such coursework, conveniently and inexpensively, in local community colleges.

3.2. Program coursework

The required M.S. ASTE coursework consists of nine courses, or 27 units, with semester-long graduate classes being 3 units each. The program usually offers up to a dozen astronautics courses each semester [24]. Practically all graduate courses are available online.

To earn the degree students must take (i) four required courses (a total of 12 units); (ii) three core elective courses (9 units); and (iii) two technical elective courses (6 units).

The required courses include three broad overview courses on the fundamentals of space systems; rocket and spacecraft propulsion; and space environment and spacecraft interactions. The fourth required course is in orbital mechanics. Core elective courses are chosen from the space-focused courses offered by the program.

The remaining two technical electives could be selected from these space courses or, if desired, from graduate courses outside the home department. The majority of students choose technical electives from the offerings by the M.S. ASTE program as these courses are often among the main reasons for their enrollment in the program in the first place.

Practically all graduate science and engineering courses from other departments are automatically approved as technical electives except for a small number of courses in non-traditional areas such as management of engineering projects and alike. The Master of Science in Astronautical Engineering degree is not a degree in system engineering, system architecting, or space studies [2]. Students with particular interests in such areas are advised to change their major to meet their educational objectives.

Table 1
Astronautics courses offered for graduate credit. Elective courses are grouped thematically.

Course
required
Spacecraft System Design
Space Environment and Spacecraft Interactions
Orbital Mechanics I
Rocket and Spacecraft Propulsion
core electives and electives
Orbital Mechanics II
Space Navigation: Theory and Practice
Solar System Navigation
Spacecraft Attitude Dynamics
Spacecraft Attitude Control
Liquid Rocket Propulsion
Solid Rocket Propulsion
Advanced Spacecraft Propulsion
Physical Gas Dynamics I, II
Space Launch Vehicle Design
Spacecraft Structural Dynamics
Spacecraft Structural Strength&Materials
Spacecraft Thermal Control
Spacecraft Power Systems
Systems for Remote Sensing from Space
Spacecraft Sensors
Design of Low Cost Space Systems
Space Studio Architecting
Entry and Landing Systems for Planetary Exploration
Human Spaceflight
Human Factors in Spacecraft Operations
Spacecraft Life Support System
Safety of Space Systems and Space Missions
Reliability of Space Systems
Safety of Space Operations
Plasma Dynamics I, II
Computational Plasma Dynamics

A typical 3-unit course consists of 13–14 weekly three-hour lectures and two exams, midterm and final. It requires approximately six hours of additional self-studies each week. Instructors and teaching assistants hold regular office hours to help students. Self-studies include required and recommended reading and weekly homework assignments as well as term papers and projects when appropriate.

Some core elective courses provide introductions to spacecraft subsystems and do not require prerequisites. More specialized courses have prerequisites. For example, a course in advanced propulsion would require, as a prerequisite, an introductory course in propulsion, and a course in space navigation would require an orbital mechanics course.

Some students, particularly those with aerospace Bachelor's degrees, have been exposed during their undergraduate studies to subjects covered by the required courses such as, for example, rocket propulsion and orbital mechanics. In such cases, the required courses are waived, and students take additional technical electives instead. A Master's thesis is not a requirement but an option for on-campus students. For online students, writing a thesis is not practical.

Table 1 shows the current list of astronautics courses offered for graduate credit. All required courses are available once or twice each year. The M.S. ASTE program offers core elective and elective courses every year or every two years, depending on student interest [24]. The existing coursework covers many space technology areas. We strive to introduce new engineering fields to close current gaps in the curriculum. For example, the areas of recent growth included human spaceflight and safety and assurance of space missions.

The availability of qualified instructors, budgets, and constraints of distance education infrastructure limit the introduction of new courses. Even maintaining the current offering of nearly 30 astronautics courses presents a major operational challenge since our instructors occasionally develop scheduling conflicts or relocate to other parts of the country to pursue their professional careers.

3.3. Areas of concentration

Students themselves determine the sequence of courses to take, with the help of faculty and staff advisers. Many begin their studies with the required courses. These broad courses help them better understand the scope of space technology. The students may subsequently change their initial selections for specialized coursework based on improved knowledge of the role of various engineering areas in space systems and operations.

Typically, students focus their studies in the desired areas by selecting corresponding core and technical elective courses. The thematic grouping of currently offered courses (Table 1) suggests possible areas of concentration. The USC catalog lists such areas as spacecraft propulsion, spacecraft dynamics, space system design, spacecraft systems and operation, space applications, safety of space systems, and human spaceflight [24]. Some elective courses contribute to studies in multiple areas. For example, the program suggests a course in space launch vehicle design for those interested in spacecraft propulsion and spacecraft systems and operations.

Some areas of study are traditional such as propulsion and space dynamics. Other suggested concentrations are in space technologies and operations that are becoming increasingly important. Twenty years ago, work in human spaceflight was mainly done by NASA and a small number of industrial contractors. Today, several companies advance their human spaceflight programs, fetching astronauts to orbit on a commercial basis and planning an expansion of human presence in space for work and pleasure. Realizing the importance of human spaceflight, USC and several other universities added former astronauts to their faculty to develop and offer the corresponding coursework.

Another rapidly growing area of space mission assurance, safety, and reliability [25-27] urgently needs expansion of the related engineering education. With the rapid growth of commercial space, the number of companies building and operating satellites and providing space launch services skyrocketed. Many companies entered the field, including startups, to pursue various space applications and develop space technology. Thousands of satellites are launched every year, resulting in the challenge of managing space traffic and assuring safe operations. At the same time, government agencies are slow to establish supportive regulatory environments in this highly specialized and demanding area of technology.

To respond to this need, the USC M.S. ASTE program has outlined an area of concentration in the safety of space systems. Today, three courses are offered on the safety of space missions and operations and reliability of space systems. This domain thrust is still in the development stage. The addition of a few new related courses to the already developed coursework should allow the establishment of a graduate certificate in space safety engineering in the future, which would contribute to the needs of the space enterprise.

4. Program instructors, students, and online education

4.1. Full-time faculty and part-time lecturers

The Master of Science in Astronautical Engineering program combines regular full-time faculty and part-time instructors. The full-time faculty primarily focus on basic science and technology such as gases and plasmas, space environment and space science, human spaceflight, and fundamentals of spacecraft design and rocket and spacecraft propulsion. Instruction in many specialized topics of satellite subsystems relies on part-time lecturers who are recognized practicing experts in the industry and government space research and development centers. They bring important real-world experience in rapidly changing areas of technology. Several part-time instructors with strong academic records are promoted to adjunct faculty.

The Los Angeles area offers access to the unmatched wealth of first-rate specialists in space technology. Fig. 3 shows many books published by USC Astronautics faculty and lecturers. The part-time instructors are a great strength and pride of the program.

Fig. 3. Some books by USC Astronautics faculty and lecturers.

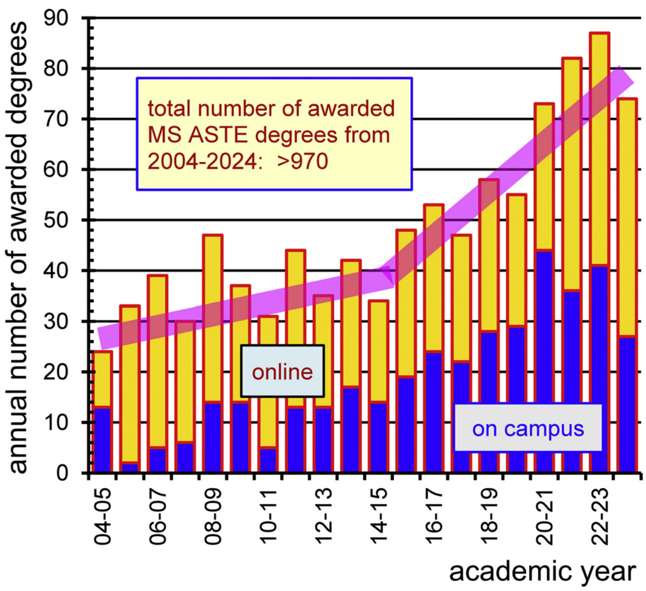

Fig. 4. Annual numbers of awarded Master of Science in Astronautical Engineering degrees to students studying part-time online (upper light bars) and full-time on-campus (lower dark bars) since the founding of the independent Department of Astronautical Engineering at USC in 2004. The total number of the awarded Master's degrees (as of summer 2024) approaches one thousand.

They work in government centers, industrial legacy powerhouses, and innovative small space companies, including The Aerospace Corporation, NASA's Jet Propulsion Laboratory, Boeing, Lockheed-Martin, Northrop-Grumman, Aerojet-Rocketdyne, Microcosm, and Space Environment Technologies.

4.2. Master's students

The M.S. ASTE program attracts both full-time on-campus students and students who work full-time and study part-time. Full-time students usually take three courses each semester and achieve their degrees in 1.5 years. Full-time working students who study part-time typically take one course (sometimes two) per semester. For them, it takes 3–5 years to earn the degree. They study through VSOE's Distance Education Network, DEN@Viterbi, even if they reside within a driving distance from the campus near downtown Los Angeles. Many Master's classes take place in the evenings which allows working students to occasionally attend lectures in person.

Online studies toward M.S. ASTE and DEN operations and facilities are described in detail in [3]. It is important that one can earn the degree without the need to ever visit the campus. Many students would fly, however, to Los Angeles to attend festive commencement ceremonies and receive their diplomas in person [28].

The educational background of astronautics students is truly diverse as the program does not require aerospace-related undergraduate coursework and admits students with Bachelor's degrees in hard sciences and all areas of engineering. Some online students already have their Master's degrees in non-space areas of engineering, and they successfully work in the space industry. Gaining a better understanding of space-specific concepts and technologies by obtaining the M.S. ASTE degree often opens pathways for advancing to leadership positions in major space programs and system engineering. In addition, students with doctorates in science and engineering as well as medical doctors sometimes enroll in the program to improve their chances of being selected for astronaut training.

Fig. 4 shows the annual numbers of the awarded Master of Science in Astronautical Engineering degrees. Today, the program graduates consist of roughly equal numbers of full-time and online part-time students. As of summer 2024, the total number of awarded M.S. ASTE degrees since the establishment of the independent department in 2004 approaches one thousand (it is larger than 970). In addition, more than one hundred Master's degrees in aerospace engineering with a specialization in astronautics had been awarded before 2004. Today, the Master's program brings about $6 M in tuition revenues annually.

The number of students who work full-time and study online (upper light bars in Fig. 4) remained relatively steady throughout the two decades. Initially, the overwhelming majority of such students worked at legacy space and defense companies (Boeing, Northrop-Grumman, and others) and government research and development centers (NASA, Air/Space Force). Today, increasing numbers of students have been coming from smaller, space-focused companies.

Since the inception of the department, the number and fraction of full-time on-campus students increased significantly (lower dark bars in Fig. 4). This reflects the growing program reputation which has overcome the initial reluctance by "freshly" graduating students with Bachelor's degrees to enroll in a pure space-focused astronautical engineering program, viewed as a smaller niche by some. Then, they chose the departments awarding traditional aerospace degrees. The space industry significantly expanded during the last two decades (Section 6 below), and students now feel comfortable pursuing a degree in astronautical engineering. In addition, students are eager to participate in the department's student groups, particularly the Liquid Propulsion Laboratory [14,15], and take advantage of research opportunities at the Space Engineering Research Center [20]. Interactions with and mentorship by full-time faculty remain indispensable for the educational experience of on-campus students.

A fraction of full-time on-campus M.S. ASTE students are in the Progressive Degree Program, or PDP (sometimes referred to as the 4 + 1 program). In this program, high-performing upper-division undergraduate USC students can earn some credits toward engineering Master's degrees by enrolling in graduate courses while completing their Bachelor's degrees. Consequently, a student can obtain both a Bachelor's degree and a Master's degree after 5 years of full-time studies rather than after the typical 4 years of undergraduate studies followed by 1.5 years in a graduate program. Students can also combine their non-aerospace Bachelor's major with a Master's degree in astronautical engineering to prepare for space-engineering careers. Today, PDP students account for one-quarter of Master's degrees awarded to full-time on-campus students.

Many space-related government and industrial programs in the United States are subject to export control International Trafficking in Arms Regulations (ITAR) [29]. These regulations resulted, in part, from the evaluation (unanimous bipartisan "Cox Report") of technology export incidents by the select committee of the U.S. Congress [2,30]. Violations of ITAR by aerospace and defense companies [1] make any meaningful reform of these regulations politically controversial and thus unlikely in the near future.

All university classes, including in astronautics, are open to students regardless of their nationality. Outside the coursework, participation in research and development projects that are externally funded by government agencies and industry must often comply with the ITAR restrictions. These regulations require involved students to be U.S. persons (in the language of the statutes). In addition, it is harder, but not impossible, for international students to find internships and later, after graduation, employment in the space industry.

Publications [1-3] discuss some effects of ITAR on the Master's program in astronautics. The overwhelming majority of our online students work in the United States. Consequently, they are U.S. citizens or permanent residents. The fraction of foreign nationals among full-time on-campus M.S. ASTE students is smaller than in many other engineering departments of the university. Students from foreign countries are aware of the ITAR restrictions and thus often choose other engineering majors. Nevertheless, foreign students enroll in the M.S. ASTE program. They also include those on government fellowships from their home countries. Since 2004, students from nearly twenty countries in Asia, the Americas, Europe, and Africa earned degrees in astronautical engineering [2,3].

4.3. Role of distance education

Continuing education with high-quality online coursework delivery plays a particularly important role in workforce development in the U.S. industries. Student interest in online education continues to grow. At the same time, changes in industry have made a Master's degree desirable and even indispensable for a successful lifelong technical career. Consequently, many leading technology-oriented companies and government centers hire graduating engineers with Bachelor's degrees and support their pursuit of Master's degrees part-time while working full-time. Tuition coverage for such studies has become part of standard compensation in space and defense industries.

Online education also opens a way for engineers who obtained their Bachelor's degrees five, ten, or more years ago to resume their education part-time and earn a graduate degree. Such studies improve chances for "lateral moves" to more attractive and interesting areas of work within large companies as well as for promotion in a highly competitive environment.

The USC Viterbi School of Engineering began developing modern distance education, a concept of a "university without walls," in the late 1960s [12]. The Federal Communications Commission granted permission for using transmitters on Mount Lee located only one hundred meters away from the iconic Hollywood Sign seen from Los Angeles. VSOE's Instructional Television Network (ITV) inaugurated direct television broadcasting (telecasting) of courses to local aerospace companies in the Greater Los Angeles area in 1972. The course delivery technology has been evolving throughout the years. In the 1990s, transponders on geostationary satellites extended ITV's reach to students outside Southern California. Finally, the Distance Education Network, today's DEN@Viterbi, transitioned to "webcasting," streaming compressed video and audio over the Internet [2,3]. Today, the Viterbi School offers over 40 graduate engineering degrees online.

Distance education is particularly convenient for working professionals who balance their work responsibilities (sometimes with lengthy job-related travel), other professional activities, and family life. The full-time students attend class lectures on campus that are being simultaneously webcast live to online students. DEN technicians then place the captured webcasts on the School's servers. While some online students watch lectures live on their desktop computers, laptops, tablets, and mobile devices, others view them asynchronously at convenient times.

All students, on-campus and online, have full unlimited access to all class-related lectures and other materials. They submit their homework and receive graded homework electronically. Full access to the recorded lectures until the final exam at the end of the semester offers excellent opportunities for reviewing various topics, especially those presenting difficulties, as many times as desired. These well-developed distance education capabilities proved particularly helpful during the recent Covid pandemic when remote learning temporarily replaced in-person instruction.

As a matter of policy, the Viterbi School of Engineering does not distinguish between on-campus and online students. The requirements for the degrees, admission to the programs, coursework, homework, exams, and evaluation of student performance are identical for all students. Online students have access to instructors, teaching assistants, and classrooms as their on-campus peers. All graduate students are held to the same standards and are expected to show the same dedication toward their education.

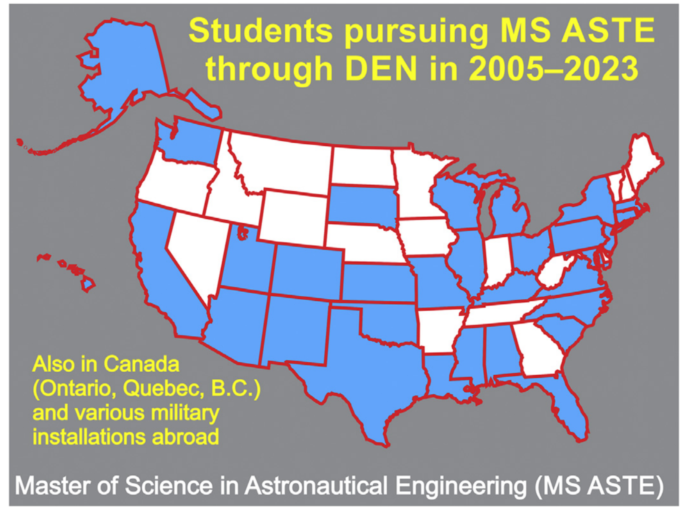

Fig. 5. Students pursuing Master of Science in Astronautical Engineering degrees online through DEN@Viterbi reside in many states (dark color) as well as in Canada and are stationed at military installations abroad.

Today, about one-half of M.S. ASTE graduates are online students (Fig. 4). Fig. 5 shows the geographic reach of the program. Astronautics students work all over the United States as well as in Canada. Students on active military duty sometimes study in foreign countries where they are deployed. In addition to early career officers, the M.S. ASTE program attracts those who plan to leave the military service in their 30s and 40s. They prepare for new civilian careers in industry, with space engineering being among the appealing areas. More details of the structure and operations of the online education program in astronautics are provided in [3].

5. M.S. ASTE and national aerospace programs

The American Society for Engineering Education, ASEE [31], compiles the national statistics in aerospace engineering education [32]. In addition to more than 70 ABET-accredited aerospace-related Bachelor's degree programs in the United States (Fig. 1), ASEE identified 52 programs that awarded aerospace-related Master's degrees in the academic year 2021–2022 [33]. This number of programs includes aerospace engineering and aeronautical engineering degrees as well as degrees in "aeronautics and astronautics." In a quirk of accounting, ASEE lists M.S. ASTE among "other engineering disciplines" [32]. (ASEE counts the Master's program in astronautical engineering at the Air Force Institute of Technology in the aerospace category. The Institute usually awards one dozen degrees annually.)

Fig. 6 (top) shows the annual numbers of nationally awarded Master's degrees (without USC M.S. ASTE) in the United States in aerospace-related areas from 1999 to 2022 [34-40]. (Note that statistical data become available with delays, especially on the national level.) The numbers were nearly flat at the levels of 700 and 1100 per year during 1998–2003 and 2005–2010, respectively. They reached 1400 per year around 2011 and remained constant for several years. The last five years show a small uptick to 1500 in the annually awarded degrees.

Fig. 6 (bottom) shows the ratios of USC's M.S. ASTE degrees to the number of aerospace-related degrees awarded annually in the

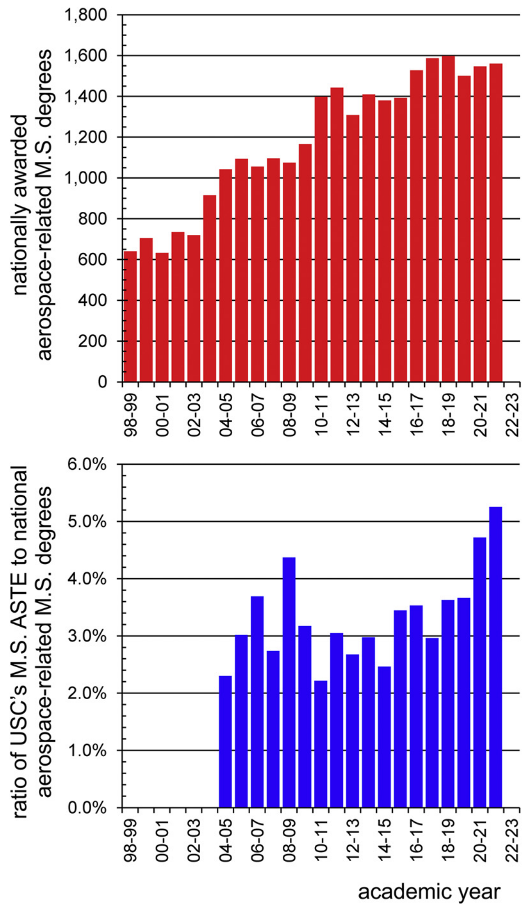

Fig. 6. Top: annual numbers of Master of Science degrees awarded in the United States in aerospace-related areas from 1999 to 2022 (based on ASEE data [34-40]). USC's M.S. ASTE is not included in these numbers in a quirk of accounting. Bottom: the ratios (expressed in percentages) of USC's M.S. ASTE degrees to the number of aerospace-related degrees (figure top) awarded annually in the United States since the founding of the independent Department of Astronautical Engineering in 2004. For 52 programs listed by ASEE, the average aerospace engineering program would account for about 2% of the total number of Master's degrees.

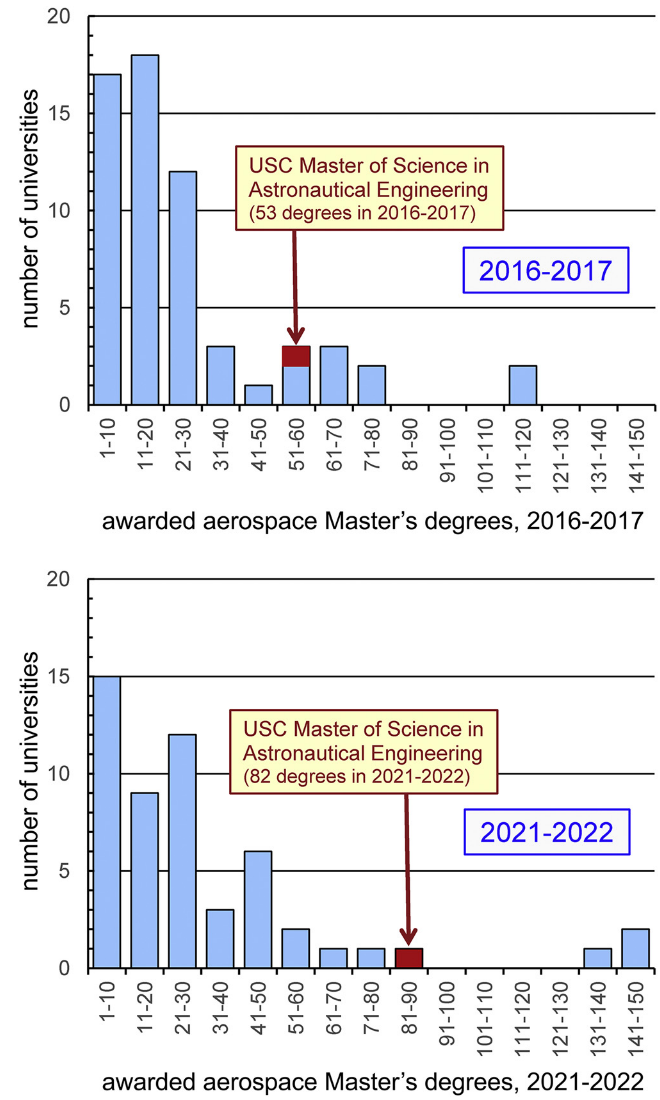

Fig. 7. Distribution of the numbers of Master of Science degrees awarded by universities in the broad aerospace area in the United States in academic years (top) 2016–2017 [3,41] and (bottom) 2021–2022 (based on ASEE data [33]). The USC's M.S. ASTE program advanced from sharing the eighth and ninth places in size in 2016–2017 to the fourth pace in 2021–2022.

United States since the founding of the independent Department of Astronautical Engineering in 2004. For many years, this fraction was at the level of nearly 3 % which is larger than the average aerospace-related program in the country. (The average size would be close to 2 % for 52 programs.). During the last two years of the available national data, academic years 2020–2021 and 2021–2022, the ratio of USC's degrees accounted for 4.5–5 %, more than twice as large as the average aerospace-related Master's degree program. The USC share would be 5 % or above in the academic year 2022–2023.

ASEE does not capture the separate numbers of awarded degrees in space-focused engineering. Therefore, one can only compare USC's M.S. ASTE program with other Master's programs in the broad aerospace-related field dominated by non-space areas. Fig. 7 shows the size distributions of such programs in awarding aerospace-related Master's degrees in the United States in the academic year 2016–2017 [3,41] and the year with the latest available data, 2021–2022 (based on [33]).

These latest data for the academic year 2021–2022 show that three Master's programs dominate the aerospace field in the United States: Purdue University (awarded 149 Master's degrees in 2021–2022), Georgia Institute of Technology (143 degrees), and the University of Colorado in Boulder (131 degrees). Purdue and Georgia Tech were also the largest in 2016–2017, awarding 117 and 113 Master's degrees, respectively. University of Washington (78 Master's degrees) and the University of Colorado in Boulder (74 degrees) also stood out in size at that time [3].

The M.S. ASTE program at USC awarded 53 degrees in 2016–2017. It then shared the eighth and ninth places in size. The program advanced to the fourth place (82 degrees) in 2021–2022 (Fig. 7). One can only speculate how it would have ranked in size if only space-engineering specializations were counted—clearly, it would be among the largest.

6. Growing space enterprise and education

Today, many countries project military power, commercial interests, and national image through activities in space. It is a truly high-technology frontier, expensive and government-controlled or government-regulated due to security and safety considerations. Space-enabled technologies have become an integral part of people's everyday lives.

Space science, space exploration, and space applications have been expanding for decades. An elite club of countries that have

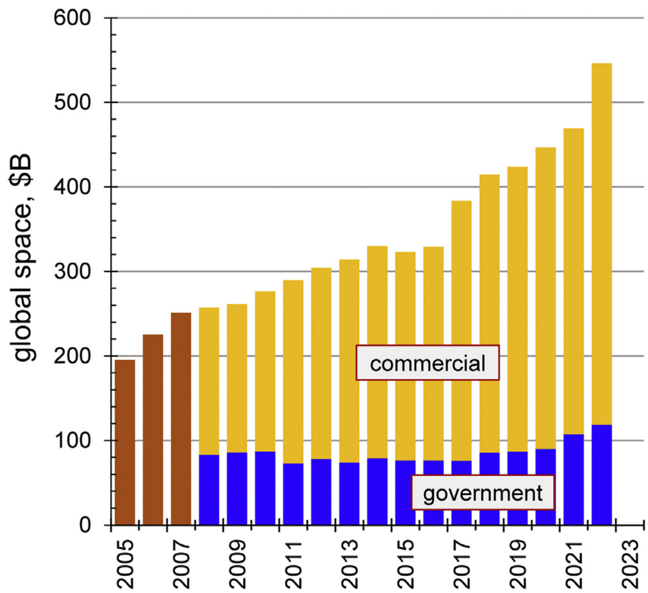

Fig. 8. Annual expenditures on space activities worldwide in billions of current (not adjusted for inflation) U.S. dollars from 2005 to 2022. The average annual growth during these 17 years was 6–6.5%. Beginning from 2008, the figure shows the breakdown between the government and commercial space activities. Based on annual data in Space Reports [43-53] compiled by the Space Foundation [42].

launched their own satellites on their own space launchers has also grown (chronologically): Soviet Union (with its space capabilities inherited by today's Russian Federation and Ukraine), United States, France, Japan, People's Republic of China, United Kingdom, India, Israel, Iran, North Korea, and South Korea. In addition, a number of European countries formed the European Space Agency which has been launching satellites since 1979.

Global space activities have dramatically grown and accounted for nearly $550B worldwide in 2022 [7]. The fast expansion of commercial space overtook government programs in the 1990s and constitutes today three-quarters of all expenditures on space. Fig. 8 shows the annual increase of 6.0–6.5 % in global space activities during the two decades since 2005 [42-53]. Such data compiled annually by the Space Foundation [42] and published in its Space Report should be viewed as approximate, illustrating the trend. Their methods of assessing expenditures by governments and industry have been evolving with time, some space programs and activities are obscure, and exchange rates of currencies fluctuate. Nevertheless, the data unmistakably show (Fig. 8) a steady increase in spending on satellite systems, space applications, and space launchers, especially in commercial space.

The growing space enterprise relies on a qualified scientific and engineering workforce. The dynamics of steadily increasing expenditures on space thus serves as a leading indicator for the size of the needed supporting educational programs. While a significant rise in space activities draws on many fields of engineering such as communications, materials, structures, and computer sciences, the core expertise in astronautical engineering (space engineering) remains the indispensable anchor that glues together the enterprise and enables further progress. The noted growth in the number of accredited undergraduate aerospace-related programs (Fig. 1) reflects this trend.

During the last two decades, a number of developing countries formed national space agencies, realizing the importance of space for the modern economy, national security, and society. Many more governments and private companies engaged in space activities by purchasing and operating commercially-built satellites for various applications. This development manifests itself in the growing representation of these entities in the International Astronautical Federation [54]. Traditional space powerhouses dwarf government space programs of the newcomers, however.

Despite the rise of commercial space (Fig. 8), government programs continue to play critically important roles. Large U.S. programs still dominate government space expenditures in the world, accounting for 59 % of a total of $118.6B in 2022 [55]. They offer broad employment opportunities with the associated need for space science and engineering education. It was noted 20 years ago that governments of industrialized countries in Europe and Japan spent in space, as a fraction of the gross domestic product, four to six times less than the United States [56]. (Historically, France has been spending somewhat more than other European peer countries.) This disparity remains today. Also, as it was twenty years ago, limited budget transparency in two very active in space countries, Russia and China, does not allow accurate assessment of their effort.

Commercial space skyrocketed since 2000 (Fig. 8), driven by the deployment of satellite constellations, series manufacturing of satellites, expanding commercial space applications, and gradually declining costs of space launch. New approaches and business practices, in particular by SpaceX and its founder Elon Musk, have played a major disruptive role, catalyzing changes and accelerating progress. Annual insurance premiums for the launch and operations of space systems have been fluctuating between $400 M and $800 M annually during the last two decades [57] in another indication of the maturing commercial space.

A large number of new companies emerged during the last two decades to pursue various commercial endeavors in space. Being often called "New Space," they advance applications that emphasize low-cost and sometimes nontraditional approaches. These companies employ many engineers and managers, including those without prior exposure to space technology. It is important for engineering educational programs to reach these "newcomers" in the growing field of space.

The space budgets of governments did not change significantly during that time (Fig. 8). Nevertheless, government programs, particularly in national security, remain critically important for the space enterprise. These programs are often performance-driven rather than focused on cost as common in the commercial world. This emphasis on performance leads to consequential associated advances in the science and engineering of spaceflight.

The last years of the administration of U.S. President Dwight D. Eisenhower more than half a century ago had shaped the structure of the American government space program, which essentially survived in its main features until the present day [56]. The program consists of three main components, civilian space, military space with some unrecognized (in public domain) elements, and space reconnaissance with largely classified budgets.

The Space Foundation assesses the U.S. government space budget at $69.9 in 2022 [58]. Its civilian component, primarily NASA ($24B) and smaller contribution of other agencies, accounts for $26.6B The space activities of the Department of Defense are estimated at $42.9, including $17.1B in unclassified spending. These military programs include space reconnaissance. Space Foundation's data also show smaller but growing government military space at $10.8B in other countries in 2022 [59].

In 2010, the Space Foundation explicitly listed three distinct U.S. space programs in its assessment. It estimated that civilian programs (dominated by NASA) accounted for 33 % of the total government expenditures in space ($64.4B at that time), military space (Department of Defense) for 41 %, and space reconnaissance (National Reconnaissance Office and National Geospatial-Intelligence Agency) for the remaining 26 % [60]. It is not unreasonable to assume that this ratio between these three U.S. government programs remains approximately the same to this day.

The budgets allocated to missile defense, about $10B annually in the United States, should also be added to space activities. Missile defense heavily relies on space. Its original programs initiated in the late 1950s led to the emergence of various space-related activities such as space situational awareness (space domain awareness), space-based systems for early warning of ballistic missile attack, and antisatellite weapons [61,62]. More and more countries invest today in strategic missile defense with significant indispensable space components and this trend will continue in the future.

The development of an engineering workforce for government programs with their inherent demand for advanced science and technology is an important consideration for any space education program.

7. Lesson learned and conclusions

The expansion of the global space enterprise during the last decades required an increase in a core engineering workforce for the space industry and government centers, with universities playing a leading role in space engineering education. The establishment of an independent space-focused Department of Astronautical Engineering at USC in 2004 was a practical approach to bringing flexibility to the educational field within the constraints of American academia. The program's steady growth in a highly competitive environment confirms the value of specialized astronautical engineering degrees for the space enterprise. The demand for space-engineering education will continue to grow, especially for companies, including New Space, pursuing commercial applications.

Online distance education helps validate the usefulness of the offered degrees. Continuing education has become the way of life for many engineers in industry, particularly in space and defense. Practicing engineers at legacy companies choose the best online Master's programs to enroll in. Their choice is often influenced by the opinions of senior engineering colleagues with much industrial experience. Therefore, if an online component of a Master's program attracts practicing engineers, then it is an indication that its degrees provide tangible value. Consequently, Internet-enabled market competition in distance education among universities is essential for assuring the quality of engineering programs. It provides a test of whether programs meet the needs of the real world. Moreover, pressures of true competition among online programs result in an additional benefit of somewhat mitigating the inevitable harm of a non-merit-based approach to education sweeping U.S. academia, e.g. [3,63-65].

The experience with the development and growth of the Master of Science in Astronautical Engineering degree program at USC points to certain features and approaches that contributed to its success. Among them is administrative independence of the program which is indispensable to reduce unproductive local "political battles" so widespread among fragmented faculty in universities. Then, the availability of qualified outside specialists from the space industry to teach specialized courses as part-time lecturers is highly beneficial and necessary but not sufficient. There should also be dedicated and knowledgeable core tenured faculty to build the program up and navigate it through the university degree and curriculum approval and maintenance processes. The program must respond to the evolving industrial needs and thus show an understanding of current industrial practices. Such knowledge is not widespread among tenured faculty who by the nature of hiring and promotion in academia focus primarily on fundamental science.

Another essential lesson is the importance of building the program's identity. This requires a clear identification of the "customer," that is parts of the space enterprise and types of engineers who would particularly benefit from the offered coursework and degrees. Clearly defining the areas of technology and putting together, "packaging," the coursework focused on these areas attract students who are searching for programs to achieve their educational objectives. In fact, their objectives are sometimes vague, and an offered well-defined path sometimes helps them in their decisions. The outlined areas of concentration in the USC M.S. ASTE program in traditional fields of propulsion, space dynamics, and space systems and in emerging areas of human spaceflight and space mission safety and reliability serve this purpose. Very few universities have responded to the clear need for educational programs in the latter two engineering areas.

Attention to student feedback represents another indispensable characteristic. Many online students have been working in the space industry for a number of years. Listening to these mature engineers and actively seeking their views could provide important insights into needs in rapidly evolving fields.

On an internal-to-university level, the financial soundness of a program in a highly competitive national and international environment is another critically important feature. Such considerations are alien, however, to many scholars in academia. It is obviously easier to obtain administrative support for experimentation and further program growth if it brings money to an academic school rather than being a burden. The financial strength can only be achieved when a program reaches a certain "critical mass" of students and continuously strives to maintain the interest of potential new students. The student experience during their studies becomes crucial as well because the program's graduates turn, with time, into its best ambassadors. Many new students from space companies and government centers learn about the program and its value from their colleagues who had received our degrees in the past.

To conclude, the experience of the Master of Science in Astronautical Engineering degree program at USC shows that it responds to the needs of space engineering workforce development. Pure space-focused departments and programs can and will contribute in an important way to the global space enterprise.

Ad Astra!

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Mike Gruntman: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

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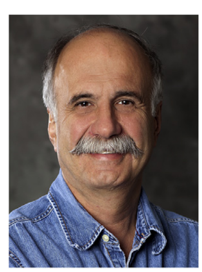

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