Chapter 2
Why Start a Small Spacecraft Program

This chapter focuses on the reasons behind starting a small spacecraft program. In this context, both programs started for educational benefit and those launched for research or other purposes are considered. An overview of reasons for program initiation is provided. Then, research and educational benefits are discussed. Broader benefits that could be provided by a small spacecraft program to society-at-large are then considered. Finally, the chapter discusses the potential of using a small spacecraft program to develop, demonstrate, or advance national space competency, before concluding.

2.1 Overview

Small spacecraft development activity is increasing significantly. Between 2000 and 2013, the number of manifested "university-class" spacecraft has increased from below 5 to over 35 [6]. In 2014, just under 30 university-class spacecraft were launched [7]. From its initial design by Jordi Puig-Suari and Robert Twiggs in 2000 [8], the CubeSat standard (one type of small spacecraft that is gaining in popularity due to its easy-to-integrate common form factor [9]) has matured from a tool for student learning to a mechanism for conducting bona fide science [10, 11] and other work [12]. Interest in CubeSats has been buoyed by low-cost [13] and free-to-qualified developer launch services, available through NASA's Educational Launch of Nanosatellites program [14] and the ESA [15]. Interest is also being generated

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This chapter is based on, revises and extends the papers "Evaluation of the Educational Impact of Participation Time in a Small Spacecraft Development Program" [1], *"Student Expectations from Participating in a Small Spacecraft Development Program"* [2], *"An Assessment of Educational Benefits from the OpenOrbiter Space Program"* [3], *"OpenOrbiter: A Low-Cost, Educational Prototype CubeSat Mission Architecture"* [4] *and "Application of Collaborative Autonomous Control and the OPEN Prototype for Educational NanoSats Framework to Enable Orbital Capabilities for Developing Nations"* [5].

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for larger-sized small spacecraft. In Europe, the ESA's Student Space Exploration and Technology Initiative [16] has generated larger spacecraft (similar to the size and mass to spacecraft facilitated in the United States by the Air Force's University NanoSat Program [17]). The European Student Earth Orbiter, for example, is a 45-kg spacecraft with dimensions of approximately 30 cm × 30 cm × 100 cm [18]. While still being built by universities [6], these spacecraft are being constructed by government [19] and industry [19]. Small spacecraft are now even being considered for lunar [20] and interplanetary use [21].

While the benefits of the form factor for missions are clear, the reasons for student involvement in the design and development of a small spacecraft are less so. In many cases, students participate and devote their skills to small spacecraft development on a voluntary basis (or at a wage level below what they could make by obtaining an off-campus job). Do these students seek to work in the space engineering field? What reasons drive those students who are studying ancillary topics? These questions are considered in the following sections that begin the process of assessing why students decide to participate in small spacecraft development and what benefits they hope to obtain from doing so.

2.2 Research Benefits

First, the reasons for why small spacecraft are developed are considered. Swartwout [22] proffers that the role of the "university-class" spacecraft (a type of spacecraft with education as its primary objective and increased risk tolerance because of the academic environment) is to provide an opportunity to try things that could not be effectively explored on larger, more expensive missions due to risk management and other concerns. Many have also used them to provide the educational experience for students envisioned by Puig-Suari and Twiggs when initially defining the CubeSat form factor [23]. As of 2014, nearly 100 educational institutions have developed a small spacecraft (some in collaboration with other institutions) and several have developed more than one craft [6]. The use of the CubeSat form factor has expanded beyond academia: over 50 CubeSats not originating from an academic institution are manifested for launch in 2013 (compared to only 30 from academia) [6]. Academic institutions are also involved in the development of a limited number of non-CubeSat-class spacecraft.

Despite what the foregoing might suggest, the development of small spacecraft isn't new. Some would argue that small spacecraft have their foundations in the earliest launches. Sputnik is pointed to, by some, as an example of a small satellite. Dickson, for example, describes it as being the "size of a beach ball" and weighing "a mere 184 lb" [24]. Thinking of something this size as small is not unsurprising, considering the size of many current and historical spacecraft. Intelsat 10, a communications satellite launched in 2004, had an initial launch mass of 5600 kg [25], for example.

It would be another 40 years, however, until the event that would drive their phenomenal growth. In 2000, Bob Twiggs (then at Stanford leading the Satellite Quick

Research Testbed project) challenged the notion of the size of a small satellite [23]. The Orbiting Picosatellite Automatic Launcher (OPAL) deployed six “hockey puck-sized” spacecraft, weighing 1 kg [23]. Following this success, Twiggs and Jordi Puig-Suari developed specifications for the CubeSat form factor (see, e.g., [26]) and developed the commonly used launcher: the Poly-PicoSatellite Orbital Deployed (P-POD) [27]. The first CubeSat was launched in 2003. To date, more than 200 CubeSats have successfully reached orbit [7, 28]; numerous others have been developed and lost to launch failures or never launched [29]. Twiggs is not stopping with the CubeSat form factor he is now working on making small satellites even smaller by developing a form factor for a satellite one-eighth the volume of a CubeSat (5 cm×5 cm×5 cm) called the PocketQub [23]. This spacecraft is targeted at enhancing high school STEM education.

Are small spacecraft just educational tools then? Thakker and Swenson [30] suggest that this may be the case. They contend that “most university satellite programs have focused more on their educational missions” than on advancing science and developing new techniques for science and engineering. Several examples of science missions exist, however, including the University of Illinois ION-1 (oxygen airglow photometer) and ION-2 (neutral hydrogen photometer) spacecraft and Taylor University’s TEST (Langmuir plasma probe, electric field boom, VLF receiver, SSD spectrometer, and transient photometer) and TU SAT-1 (Langmuir plasma probe, tether, and Nitol tether). Swartwout, however, disagreed he proffered [22], in 2004, that “university-class satellites” could be “disruptive” research platforms: they can alter the way that space research is carried out. He asserted that this disruptive capability comes from the particular strengths of research universities: students’ enthusiasm and novel ideas and the “freedom to fail” [22].

In disagreement with Thakker and Swenson’s statement only 2 years earlier, in 2012, Swartwout [31] noted that university programs have moved away from being “beepsats” (a term used to characterize spacecraft lacking “a compelling science, technology, or communications payload”) to incorporating real scientific, engineering, or other goals. These missions, he noted (in 1997), should have risk from their unique characteristics and not be an exercise in navigating complexity [32]. A university program, under these circumstances, can be beneficial to students’ educational attainment and investigate “risky and/or innovative methods” [32].

From an educational perspective, university missions are valuable to industry and others as they can and do employ the same mission analysis and design techniques [8, 33, 34] utilized by industry, military and government, preparing students for workforce entry. Chin et al. [35] proffer, however, that the standardization in the CubeSat development community is critical to the form factor’s success; this of course is atypical for space missions which (while reusing proven/qualified components) generally implement mission or program-specific designs. The notion of a more standardized approach to space missions ties in with a proposed TRL 10 paradigm, where operations of a model of spacecraft are characterized and failure conditions are well known and understood (as is, for example, typical of commercial airliners) [36].

Small spacecraft are not just valuable for educational activities, education research and training future researchers. Small spacecraft are also being used to perform bona fide research. CubeSats, for example, are pushing technical boundaries. Twiggs and Malphrus [8] provide an overview: CubeSats are using (and in some cases being used to test) advances such as plastic printed structures, deployable solar panels and technologies (such as Stanford's Hemispherical Anti-Twist Tracking System, HATTS [37]), advanced propulsion (e.g., heated Freon gas), and 3D printed propulsion.

Given the foregoing, it might seem that small spacecraft are excellent tools for both research and education. Swartwout [38], however, highlights two key problems: spacecraft projects are not responsive to university needs of creating a sustained educational program or attracting external research sponsorship. Prior to the advent of CubeSats, Swartwout proffers that schools "rarely, if ever" completed a second project after an initial success. CubeSats, he asserts, are changing this; however, it is unclear as to whether this has changed significantly, except for at a few key schools.

2.3 Educational Benefits

Educational benefits from small spacecraft come from both formal and informal learning. Formal learning occurs in lectures, readings, and other structured activities in courses and elsewhere. Informal learning comes in the form of project-based learning (PBL). PBL is a technique where students learn by doing. While the concept is by no means new (as the apprenticeship style of learning has been used throughout history [39, 40]), it is seen as a departure from the traditional lecture-based style of instruction. The benefits of PBL are seen by some as so great as to have an effect on national competitiveness on an international scale. Gilmore [41], for example, contends that STEM education will determine the future of nations and proffers that PBL and EE are critical to the United States' ability to compete globally.

2.3.1 Experiential Learning and Problem-Based Learning

Project-based learning (also known as problem-based learning or experiential learning) involves providing students with a challenge to solve or a problem to resolve. Students collect information, assess the nature of the challenge or problem, and devise and implement a plan to achieve the assigned goal or resolve the assigned problem. The utility of PBL techniques has been demonstrated for all stages of education ranging from primary to university level (see [42–47]). The use of PBL has also been favorably assessed in numerous disciplines, such as computer science [48, 49], computer engineering [50], electrical engineering [51, 52], mechanical engineering [53–55], aerospace engineering [56, 57], management [58], project management [59], and entrepreneurship [60] and marketing [61]. Small spacecraft development, in an educational setting, is inherently an exercise in PBL. Students can be involved (depending on program particulars) in the design, development, testing, and operations of the spacecraft. PBL small spacecraft programs (e.g., [47, 62]) have been shown to be effective in achieving educational outcomes.

The development of small spacecraft and CubeSats provides students with PBL style educational benefits [47, 63, 64] in their discipline of participation. From the foregoing it is clear that PBL is effective in a diverse number of disciplines relevant to small spacecraft development. It has also been shown to be effective across a wide range of educational and age levels [43, 47].

Student small spacecraft development provides participants with the opportunity to develop and hone their skills. Students will also inherently develop new 'out-of-the-box' concepts. The educational environment allows them to try these concepts and to make mistakes, on a path to success in a low-risk environment facilitated by the low mission cost levels [64].

In a college or university context, PBL can occur in several formats. Students may engage in PBL activities as part of a regular course, such as a course project [47] and a PBL course. They may participate as part of an independent or directed study [3] or to satisfy a senior design or capstone requirement [65]. They may also participate for extracurricular educational enrichment [3]. Small satellites easily integrate into a project-based learning (PBL) methodology. The PBL technique seeks to create student learning through immersion in a project. Students are tasked with overcoming foreseen and unforeseen challenges and learn during the process.

PBL has also been shown to deliver benefits in addition to driving learning about course topics. These include improved student self-image [66], creativity [67], motivation [66], material understanding [68], workforce preparation [68], job placement [69], and academic program [70] and knowledge retention [71]. Zhou [72] contends that creativity is critical for engineers. This creativity can be developed via a variety of techniques including creating a conducive environment requiring problem solving. Zhou identifies PBL as a technique that can help create engineering creativity through student-centered, self-directed collaborative exercises. To this end, an eight-step approach is proposed beginning with (1) "problem setting," incorporating, (2) brainstorming, (3) systematization, (4) thematic selection, (5) formulation of learning tasks, (6) knowledge acquisition via self-studying, (7) knowledge integration, and concluding with (8) structuring the knowledge in terms of the problem at hand.

Smith et al. [73] demonstrated a technique specifically for incorporating CubeSat development in undergraduate aerospace engineering and planetary science curriculum. Their approach is based on prior work by Crawley et al. [74] who pioneered an approach entitled "Conceive-Design-Implement-Operate" (CDIO), based upon feedback from numerous engineering education stakeholders (educators, industry, students, etc.). Smith et al. [73] expand this by asserting that there is a significant need, in aerospace engineering, for shared understanding between scientists and engineers. In the ExoplanetSat initiative, students from the Department of Earth, Atmospheric and Planetary Sciences were involved in the design process, via enrolment in the three-semester CDIO course progression. This required students to engage in a science versus engineering trade process throughout the mission, analogous to how a larger mission of this type would be performed. While this expanded the scope of interdisciplinary collaboration slightly, it still did not fully encompass all discipline types that would be required to be involved in a real-world mission of this type.

Another small satellite PBL example is provided by Rodriguez-Osorio and Ramirez [75] who presented work at the ETSI de Telecomunicación in Madrid, Spain, related to an extracurricular NanoSat project. This 21-month project was student conceived and implemented (under faculty supervision). An antenna array designed for the purpose of inter-spacecraft communication (for a CubeSat-size craft) was created and its performance characterized. Rodriguez-Osorio and Ramirez proffer that this experiment demonstrates the feasibility of implementing simulated industry-analog engineering projects with limited resources and "promising results" [20].

Prior work has demonstrated the efficacy of small spacecraft development, for student learning, in general [1, 3]. It has also considered benefits that were specific to undergraduates [76], computer science students [77], and various roles within the development group [1, 3]. More details on and an expansion of this prior work are discussed in Chaps. 8–10.

While student-involved projects may provide significant benefits (whether attempting to achieve exclusively learning goals or a combination of substantive research and education), it is important to note that they carry significant risk of project failure or less-than-complete success [78, 79]. This risk comes from conventional risk sources (e.g., delays beyond project manager control, supplier issues); many elements of conventional risk are also exacerbated by the project conditions typical of student projects (e.g., participant lack of knowledge and inexperience). Student-involved projects also incorporate their own particular risk factors driven by the academic environment (e.g., a prioritization of course work over project performance, students joining and leaving the project at semester breaks and other times). Risk and general management are, thus, crucially important. Risk, mitigation, and management are discussed further in Chap. 7.

2.3.2 Benefits of Interdisciplinary Projects

Interdisciplinary projects are typical of the modern workplace. Most undertakings of any size cannot be performed exclusively by practitioners of a single discipline or specialty. However, many student projects in an academic environment are performed within the context of a course or a degree program. Because of this, they generally involve a set of similarly trained students working on a narrowly defined topic. Even projects that span disciplines (e.g., teams participating in NASA's Lunabotics competition [80]) may be limited to only closely related disciplines (electrical, mechanical, and computer engineering, for example).

Because of this, students may not gain exposure to a true interdisciplinary project (characterized by multiple specialists collaboratively performing work related to their area of specialty) until after they enter the workforce. This may require them to unlearn practices and approaches learned while working only in discipline-constrained teams. They may also experience frustration if the process of getting up to speed in this impairs their performance during their initial period (normally including some sort of an evaluation/probation process) with a new employer whom they are trying to impress.

Involving students in interdisciplinary work prevents 'silo'-type work habits from developing; students instead learn how to work well in collaboration with others with skills divergent from their own. In addition to these general benefits, students also begin to learn the particular vernacular and work styles of the disciplines whose practitioners-in-training they collaborate with. Interdisciplinary projects may also be able to have a larger scale than those within a single discipline, offering an opportunity for project management practices and discipline-specific multiperson collaboration techniques (e.g., software version control management) to be learned and refined. All of this increases student participant preparation for workplace entry and success.

2.4 Societal Benefits

This section considers the societal benefits that can be provided by small satellites and could, consequentially, be produced by a small spacecraft program. To this end, it begins with a discussion of the benefits produced by remote sensing, a common use for satellites: the data products that can be produced and their prospective uses are considered. A brief discussion of the required technologies to produce these benefits is then provided (this was discussed in greater detail in Chap. 1). Then, a discussion of one particular mission concept that may offer particular benefit for developing countries is presented. This is followed by a discussion of the qualitative assessment of spacecraft data and a discussion of the prospective role small spacecraft can have in developing national space competency.

2.4.1 Remote Sensing Benefits, Data Products, and Their Uses

While a wide variety of data products can be generated via remote sensing (including thermal infrared imaging, multispectral imaging, microwave and LIDAR imaging, and gravitational data [81]), one of the most common is visible light imagery (and near-visible light imagery that can be produced via changing the filtering applied to standard sensing equipment).

Visible light remote sensing data is defined by its coverage and spatial and temporal resolution as well as other qualitative aspects [81]. Coverage of desired areas is clearly important. Spatial resolution is a measure of the size represented by each pixel on the imagery. The utility of spatial resolution levels ranging from submeter to over a kilometer has been demonstrated [82]. Temporal resolution is a measure of how frequently data for a given area can be reobtained (i.e., how current the data is).

For agriculture, visible light sensing data can be useful for assessing where to deploy and the deployment of fungicides and pesticides, assessing crop damage due to weather and assessing drainage patterns and designing drainage solutions [83]. The utility of both aerial and satellite imagery has been demonstrated for this purpose [81, 83, 84]. The resolution required varies by application; however, the utility of 20-m data has been demonstrated by the International Space Station Agricultural Camera [85]; the use of 10-m [83] and much higher resolution [84] data has also been demonstrated. Temporal requirements vary, based on the desired phenomena under study. In addition, data may be needed on demand for use in storm damage assessment and other cases.

Remote sensing of urban areas, such as might be used for municipal planning and other purposes, has been performed with data ranging from 100-m to 10-m and higher resolution [86]. This data can be used to determine material composition, land cover, and land use for planning and other purposes. The level of temporal coverage required varies significantly, with once-a-year resolution being acceptable for some applications and more frequent imagery (including imagery at given times) being required for others. Miller and Small [87] proffer that remote sensed imagery is particularly important for developing regions as it can serve to replace the growth and environmental condition data collected in situ (or by other means) in more developed nations. They also note the utility of remotely sensed data being unobstructive and consistent.

Remote sensed data has also been shown to be useful in responding to hazards such as earthquakes, volcanos, floods, landslides, and costal inundations. In this context, data can be used to prioritize response efforts, direct responders as well as to, in the longer term, perform risk assessments, and establish policies to prevent future issues [88].

A multitude of other uses for remote-sensed data exist, many of which would be relevant to both developed and developing nations. These include its use in aquaculture (sea farming), such as was demonstrated in India [89], and water policy [90].

2.4.2 Technologies and Mission

This section briefly highlights the technologies needed for remote sensing missions. It includes both required technologies and those with augmentative capabilities. Multiple technologies are required to support a prototypical remote sensing mission for developing countries. These include basic systems (such as attitude determination and control, the electric power system, communications, and thermal control) as well as mission-specific technologies. Some software technologies are also required to enhance mission performance: these include super-resolution, mosaicking, and task sharing between craft. Super-resolution enhances imagery beyond the physical collection capabilities of the craft. Mosaicking combines images together to produce a more ready-to-use data product and it eliminates the retransmission of overlapping areas. Task sharing between craft may be required to collect the level of data required to meet temporal and spatial coverage goals. An expanded discussion of this topic was presented in Chap. 1.

2.4.3 Collaborative Mission for Developing Countries

A collaborative mission is one prospective way that smaller countries could afford access to space as well as the sensing capabilities that they require. Such a collaborative mission could incorporate multiple spacecraft from a single country, spacecraft from multiple countries, or a combination of the foregoing. While an economic model could be devised entailing payments from one to another for services rendered, an alternate (perhaps easier to manage) approach would be to require a contribution proportionate to the level of benefit that is expected (or the attributable level of expense). This could range from some countries participating as partners in a spacecraft to others (who would enjoy more benefit) providing multiple craft.

There is no requirement that the collaborating countries be neighbors; in fact, collaboration between dispersed countries may be ideal as this may reduce contention for craft use when over a group of local collaborators' general vicinity. It would, of course, be necessary for all of the target regions to be able to be served from the selected orbits. However, the use of other resources (e.g., processing capabilities) would require only sufficient communications opportunities to exist between orbital craft.

2.4.4 Qualitative Analysis

A discussion of how to assess the utility of a particular mission approach is now presented. The quality and utility of the data and the suitability for various applications are considered.

2.4.4.1 Quality and Utility of Data

The quality and utility of remote-sensed data will be a function of several different factors. First is the quality of the collection equipment and supporting subsystems that aim, stabilize, and point it. Even if the data is of a suitably high resolution, if it is blurry or otherwise degraded, it may be of little use. Image processing techniques may be able to resolve (or mitigate the impact of) some imperfections.

Second, the number of images that can be collected of the given region in a given period of time will directly affect the prospective uses that it is suitable for. If multiple images can be captured of a given area in a support period of time, computational image enhancement [91] can be performed. The number of images that can be collected constrains the level of enhancement that will be possible.

2.4.4.2 Application Suitability

The spatial resolution of the enhanced data will be a function of the collection hardware, selected orbit, and the level of software enhancement (if any). Several considerations must be kept in mind as one is assessing the suitability of the data prospectively collected for a given application. First, of course, are the particulars of the application. Data that was suitable for one purpose within a general category (e.g., land cover assessment and planning) may not serve another (e.g., roadway planning). Thus, specific needs must be identified and the compliance of the solution with those needs assessed. Wertz et al. [8] discuss this process, both in general and in the context of an imaging spacecraft. Jensen [81] provides numerous examples of previous remote sensing missions and their capabilities.

The second consideration is the degradation of capabilities over the life of the mission (or if one partner fails to deliver their equipment for a shared cluster mission). In a cluster configuration, degradation can be gradual (as opposed to the all-or-nothing statuses provided by a single craft approach) with proper planning. In clusters, for risk mitigation purposes, critical elements should be spread between partners and orbital locations. Through this, the impact of a partner failing to deliver, pulling out during operations, or equipment failure or damage can be mitigated.

Third, the utility of a given resolution (or quality) of data should be considered relative to projected costs. Alternate prospective suppliers and/or other data collection techniques should also be considered.

2.4.4.3 Mission Approach Considerations

All of the different prospective mission approaches have benefits and drawbacks. The collaborative mission, for example, requires cooperation between countries. This may be difficult to attain and maintain. Single craft missions have a significantly increased risk due to the craft (and its critical components) representing single points of failure.

Export control regimes and various political considerations should be considered. They may limit who can work on a mission and/or impede or preclude the collaborative mission pproach. As the product of fundamental research, some university-developed spacecraft (such as the current OPEN design) may enjoy favorable treatment under US export regulations. Modified versions (created by commercial entities) or commercially developed designs may not enjoy this benefit.

Additionally, an analog to the fundamental research classification may not exist or be as favorable under other nations' laws.

Finally, technical problems, a lack of skilled staff, training issues, and other hurdles may impede deployment. This possibility should be considered in build/buy decisions. Risk is discussed further in Chap. 7.

2.5 Considerations Based on National Space Competency

Some countries will undoubtedly see small spacecraft development programs as a mechanism to increase their national space competency. In these cases, the desire to develop 'home grown' technology (or to avoid technology where continued access may be subject to the continued friendship with another nation or which is regulated by another nation's export control regime) may trump many other considerations. Chapter 3 presents a discussion of one of the key choices faced by developers in starting a program: whether to build from scratch, buy a vendor kit, or use a hybrid of the two choices. The reason for program initiation (i.e., if it is for national competency building) may, obviously, be a key factor in this type of decision.

2.6 Conclusion

This chapter has presented a discussion of why various entities and individuals decide to start (or participate in) a small spacecraft development program. It has discussed the prospective benefits from technical development, research, and education perspectives. It has also, briefly, considered the role of the program (in a national context) on this decision-making process.

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