THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF AEROSPACE ENGINEERING

DESIGN OF LOW-PROFILE DEPLOYABLE SYSTEMS
FOR UNIVERSITY CUBESATS

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Abstract

Nano-satellites are quickly becoming an important platform in space exploration and scientific exploration, and new technologies must be developed to maximize their potential. The standards set forth by the California Polytechnic University (CalPoly) CubeSat Design Specification (CDS) have helped to proliferate the spread of CubeSats as a low-cost method to access space. Scaling of technologies to fit small packages is required for even greater use of the CubeSat platform. The Student Space Programs Laboratory (SSPL)’s Orbital System for the Investigation of the Response of the Ionosphere to Stimulation and Space Weather (OSIRIS) spacecraft requires the use of a deployable boom for its science experiment, and a boom that satisfies the requirements is not commercially available to SSPL. This work addresses the development process of the OSIRIS deployable boom system through a systems engineering and engineering design approach to increase the technology readiness level (TRL) of the system concept and to conclude with a feasible design based on prototype evaluation and application of practical experience. The methods presented here include research and benchmarking, requirements formulation, concept development, 3D computer-aided design (CAD) modeling, formal trade studies through a pairwise comparison matrix and Pugh matrix, and rapid prototyping using RepRap prototyping machines at The Pennsylvania State University.

The result of this development project is a concept based upon prototype evolution and consideration of the various system components and interfaces. The final design concept includes a stand-alone cassette to handle the boom stowage and deployment and housing of the Hybrid Plasma Probe (HPP), but relies upon an external method for stowing the triax cable on the outside of the spacecraft. This concept is rooted in the results of prototype testing and experience, but requires additional prototyping and environmental testing before it is ready for inclusion in the OSIRIS flight model. The system is also anticipated for application in the OSIRIS-3U satellite out of SSPL. The system is also expected to add to the regiment of CubeSat technologies available in the public sector so that additional CubeSat missions may be enabled.
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<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>HPP</td>
<td>Hybrid Plasma Probe</td>
</tr>
<tr>
<td>OSIRIS</td>
<td>Orbital System for the Investigation of the Response of the Ionosphere to Stimulation and Space Weather</td>
</tr>
<tr>
<td>SSPL</td>
<td>Student Space Programs Laboratory</td>
</tr>
<tr>
<td>CalPoly</td>
<td>California Polytechnic University</td>
</tr>
<tr>
<td>RF</td>
<td>radio frequency</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>ConOps</td>
<td>Concept of Operations</td>
</tr>
<tr>
<td>HAARP</td>
<td>High Frequency Active Auroral Research Program</td>
</tr>
<tr>
<td>EISCAT</td>
<td>European Incoherent Scatter Scientific Association</td>
</tr>
<tr>
<td>TRL</td>
<td>technology readiness level</td>
</tr>
<tr>
<td>CAD</td>
<td>computer-aided design</td>
</tr>
<tr>
<td>SEDTAPP</td>
<td>School of Engineering Design, Technology, and Professional Programs</td>
</tr>
<tr>
<td>OLite</td>
<td>OSIRIS Lite</td>
</tr>
<tr>
<td>OLite 2</td>
<td>OSIRIS Lite 2</td>
</tr>
<tr>
<td>HASP</td>
<td>High Altitude Student Platform</td>
</tr>
<tr>
<td>LSU</td>
<td>Louisiana State University</td>
</tr>
<tr>
<td>CSS</td>
<td>CubeSat Simulator</td>
</tr>
<tr>
<td>CDS</td>
<td>CubeSat Design Specification</td>
</tr>
<tr>
<td>ITO</td>
<td>indium tin oxide</td>
</tr>
<tr>
<td>GPRSO</td>
<td>GPS Radio Occultation</td>
</tr>
<tr>
<td>TEC</td>
<td>total electron content</td>
</tr>
<tr>
<td>NRL</td>
<td>Naval Research Lab</td>
</tr>
<tr>
<td>P-POD</td>
<td>Poly-PicoSatellite Orbital Deployer</td>
</tr>
<tr>
<td>CoM</td>
<td>center of mass</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>TML</td>
<td>total mass loss</td>
</tr>
<tr>
<td>COM</td>
<td>communication subsystem</td>
</tr>
<tr>
<td>CDH</td>
<td>command and data handling subsystem</td>
</tr>
<tr>
<td>GNC</td>
<td>guidance, navigation, and control</td>
</tr>
<tr>
<td>COTS</td>
<td>commercial-off-the-shelf</td>
</tr>
<tr>
<td>SMA</td>
<td>shape memory alloy</td>
</tr>
<tr>
<td>STEM</td>
<td>storable tubular extendable member</td>
</tr>
<tr>
<td>CTM</td>
<td>collapsible tubular mast</td>
</tr>
<tr>
<td>MEROPE</td>
<td>Montana EaRth-Orbiting Pico-Explorer</td>
</tr>
<tr>
<td>PLA</td>
<td>polylactic acid</td>
</tr>
<tr>
<td>SDL</td>
<td>Systems Design Lab</td>
</tr>
</tbody>
</table>
Acknowledgments

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Outside of this project, Dr. Richard Devon and other faculty members in the Engineering Design Program and in the Science, Technology, and Society Department have offered up a wealth of wisdom that is unmatched and, because of them, I can truly say that my view of the world is much more rich and diverse than what many students hold when they leave. I owe my vision of my world and my desire to affect it to all of you.

Finally, I would like to thank Brian Schratz, Allen Kummer, and the other members of the Student Space Programs Lab for their dedication, hard work, and drive to be great engineers and also enjoy what it is that makes challenges interesting. My team has been excellent over the years, and I owe them a great deal. My family and friends have also been supportive of my goals over the years, and I thank them.

As I look back on my time here at Penn State, I will miss each and every one of you, but the journey is not over. I look forward now to stepping into the world and taking what you have given me and using it to affect change and continue on the quest to make mankind great.
Chapter 1

Introduction

Nano-satellites have triggered a significant paradigm shift in access to space. In the past, only large corporations and governments could launch satellites into orbit because of the significant resources required. This is changing, however, as smaller, more affordable satellites are putting access to space into the reach of smaller entities and amateurs. They are also allowing companies and organizations to do research at a reduced cost, saving valuable resources. A whole classification of miniature satellites (see Figure 1.1) have emerged to encompass the variety of sizes that are now possible. Of course, the technical challenges of scaling a highly complex and advanced system into a small package are non-trivial.

1.1 University CubeSat Program

The CubeSat program was initiated by the California Polytechnic University (CalPoly) and Stanford University “to develop a standardized space platform for academic satellite projects” (AMSAT, 2010). Classified as nanosatellites, single CubeSat units, or “1-U” CubeSats, measure $10 \times 10 \times 10$ centimeters and have a mass of up to 1.33 kilograms. Multiple 1-U units can be combined to form larger CubeSats. All nanosats must conform to standards set forth by CalPoly in order to be classified as CubeSats and are supported by relatively openly available information and other CubeSat developers. In a sense, the CubeSat community has created a semi-open-source model for orbital technology. It has broken down — or at least reduced — the barriers to entry for many groups that can benefit from space-based research or that have an interest in injecting spacecraft into orbit.

<table>
<thead>
<tr>
<th>Type</th>
<th>Mass Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minisat</td>
<td>100 - 500 kg</td>
</tr>
<tr>
<td>Microsat</td>
<td>10 - 100 kg</td>
</tr>
<tr>
<td>Nanosat</td>
<td>1 - 10 kg</td>
</tr>
<tr>
<td>Picosat</td>
<td>0.1 - 1 kg</td>
</tr>
</tbody>
</table>

Figure 1.1: Scale of miniature satellites
1.2 The Pennsylvania State University OSIRIS Program

The Student Space Programs Laboratory (SSPL)'s Orbital System for the Investigation of the Response of the Ionosphere to Stimulation and Space Weather (OSIRIS) CubeSat is a student-run program investigating the effects of space weather in Earth’s ionosphere on radio frequency (RF) communication. RF communication is a topic of interest because of the significant level to which we all depend upon it. Technologies from Global Positioning System (GPS) to satellite TV and even military long distance operations depend on satellite linkages. Furthermore, satellites themselves depend on inter-spacecraft data links and ground station uplinks and downlinks in order to function. Interruption of satellite radio communications due to solar events and other atmospheric disturbances would pose not only an inconvenience for our modern way of life but could also risk significant infrastructure loss and security breaks for weeks or even months or years (Tracton, 2011).

Examination of ionospheric plasma events induced by solar disturbances or by man-made means requires coordination between ground facilities and the overhead OSIRIS spacecraft, of which three would exist in orbit during the mission. A graphical illustration of the Concept of Operations (ConOps) is presented in Figure 1.2. OSIRIS takes \textit{in situ} measurements of naturally occurring phenomena, but because such events are unpredictable, man-made events are scheduled when OSIRIS orbits over the High Frequency Active Auroral Research Program (HAARP), Arecibo, or European Incoherent Scatter Scientific Association (EISCAT) facilities. During these scheduled science events, the facilities bombard the ionosphere with high power radio waves to cause localized events for the purpose of \textit{in situ} measurements.

![Figure 1.2: OSIRIS ConOps](image)

1.3 Tools and Methods Used in this Work

Development of the OSIRIS boom is an undertaking that involves stakeholders across the entire project and which involves significant risk. Therefore, in the interest of maximizing the chance of success and opening possibilities for future incorporation of the result into other programs, this project employs systems engineering practices and follows a detailed engineering design process.
The project also relies heavily upon industry-standard tools while also exploring emerging design technologies in an effort to remain up-to-date and relevant to future applications.

The role of systems engineering is to “guide engineering of complex systems” and provide a “robust approach to design, creation, and operation of complex systems that typically involve many engineers and stakeholders” (Bilén, 2011). Typically, space systems engineering involves trade-offs in adding additional complexity to a system, but the scope of this deployable system is sufficiently isolated within the overall system architecture that this additional complexity may be considered negligible. Because of the complexity of the OSIRIS spacecraft bus and mission architecture, systems engineering is a critical component to successful planning and execution at the system and subsystem level, but it must also flow down to component design, especially when a component such as the deployable boom system is itself a complicated system. For the success of the deployable boom system’s end product, the engineer must have a thorough understanding of its operational context, its requirements, and its life cycle — all of which mandate a multidisciplinary understanding of the overall system.

Space systems engineering also includes an understanding of technology readiness levels (TRLs), which are a measure of a system’s flight readiness based upon its design heritage, testing, flight heritage, and reliability. A basic outline of TRLs is presented in Table 1.1. Most of the OSIRIS components and system are at a TRL of between 3 and 5, depending on whether or not they have been demonstrated as a prototype in simulated environments. Until this point, the deployable boom system for OSIRIS does not exist in any form, and similar systems in existence are either not directly scalable to the needs of OSIRIS or are not directly translatable to meet the mission needs. The goal of this project is to increase the TRL of the deployable system to at least 4 so that integration with the OSIRIS design may begin in parallel with continued development of the boom.

Table 1.1: Description of the TRLs (Mankins, 1995, p. 1)

<table>
<thead>
<tr>
<th>TRL Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRL 1</td>
<td>Basic principles observed and reported</td>
</tr>
<tr>
<td>TRL 2</td>
<td>Technology concept and/or application formulated</td>
</tr>
<tr>
<td>TRL 3</td>
<td>Analytical and experimental critical function and/or characteristic proof-of-concept</td>
</tr>
<tr>
<td>TRL 4</td>
<td>Component and/or breadboard validation in laboratory environment</td>
</tr>
<tr>
<td>TRL 5</td>
<td>Component and/or breadboard validation in relevant environment</td>
</tr>
<tr>
<td>TRL 6</td>
<td>System/subsystem model or prototype demonstration in a relevant environment (ground or space)</td>
</tr>
<tr>
<td>TRL 7</td>
<td>System prototype demonstration in a space environment</td>
</tr>
<tr>
<td>TRL 8</td>
<td>Actual system completed and flight qualified through test and demonstration (ground or space)</td>
</tr>
<tr>
<td>TRL 9</td>
<td>Actual system flight proven through successful mission operations</td>
</tr>
</tbody>
</table>

Efforts are taken to follow a regiment in the process of designing the boom system in order to avoid common engineering process errors. Experience suggests that many engineering students tend to follow initial intuitive design decisions without seriously considering alternative plans of action or they become trapped in tunnel vision when problems do arise. These situations result in the student being blindsided by major flaws or problems or in a flawed design because the product’s context was never fully realized.

In order to avoid such issues, the following steps are carried out through the design and prototyping process:

1. Creation of a detailed problem definition, objective, and criteria for success;
2. Research and benchmarking of existing technologies or previous work on similar problems;

3. Generation of solution strategies and concepts, involving multiple parties and all stakeholders;

4. Detailed trade study analysis of top-level concepts, involving multiple parties and all stakeholders;

5. Detailed design of selected concept;

6. Low-level trade studies of concept component decisions and continued design;

7. Prototype and examination of current design;

8. Discussion of design failures and improvements; and

9. Iteration of Steps 5 through 8.

Trade studies are of particular interest because of their usefulness in minimizing design decision subjectiveness, communicating design rationale, and reducing risk, and also because of their lack of serious implementation in many projects at the student level outside of some instruction at the introductory Engineering Design level and senior design courses. A trade study involves the examination of design options and the metrics — or criteria — by which they are judged and results in a relative scoring of strength for each option. In cases with few options or metrics, the study may be accomplished through written examination of the options, i.e., looking at the “pros” and “cons,” or through simple scores, i.e., a “+” or “−” for each option and metric, to quickly make appropriate decisions. For more detailed analyses, a numerical method is used to generate scores for each option.

In this case, for the decision of deployment architecture, the study employs two matrices that examine the metrics and the design options. The first matrix, called a pairwise comparison matrix, determines the relative strength of each metric in the overall decision. For simple studies this step may not be necessary, but in complex situations the various metrics seldom carry the same weight. For example, the cost of a system and the system mass may not have the same importance. The matrix is a square matrix with the rows and columns representing the metrics, the same along both axes, and each pair of symmetric cells representing the pairing of two metrics carries a weight that represents the comparative strength between the two metrics. When the matrix is completed, the individual scores are summed across the rows to acquire a final score for each metric, which can then be normalized. The second matrix, called a Pugh matrix, accepts scores for each option and metric from the user. The matrix then considers the relative weights of each metric and produces a score for each option, indicating that option’s strength. Complete instructions for the usage of the matrix templates used by SSPL are available in the SSPL document library under file name Trade Study Matrix Template, and the completed matrices for this project are available in Appendix B and may be useful for illustration.

All modeling is done in SolidWorks 2011 computer-aided design (CAD) software using the Penn State College of Engineering academic license. SolidWorks is a powerful tool for creating 3D virtual models of the design so that potential issues and flaws can be recognized prior to construction and so that relations among complex components can be identified and resolved. It also allows for generation of detailed 2D drawings that not only allow fabrication but also serve as an archival tool in the rare event of data loss.

A powerful tool emerging in recent decades is 3D printing, often referred to as rapid prototyping in the context of creating non-functional parts on a short turnaround time. As 3D printed parts become increasingly detailed and functional while also maintaining a short production time relative to subtractive manufacturing processes, the barrier between “rapid prototyping” and “3D printing” of functional parts starts to fade. Currently, the RepRap community is aiming to develop an open source 3D printing system that can be built and operated at low cost.
by anyone with basic skills and a desire to print objects. This emerging technology compliments
the low-cost and open-source nature of CubeSats. RepRap printers have been constructed and
are currently operated by students at Penn State,¹ and these printers have formed the basis for
rapid production of design prototypes of the OSIRIS boom. Ease of access to the printers and
quick print times have allowed for rapid evolution of the design.

1.4 Contribution of this Work

The CubeSat community largely operates on the flow of knowledge across developers, creating
what could be considered an open source engineering knowledge base. Many designs are freely
available on the Internet, and developers are typically happy to discuss problems with fellow
developers. This work provides a contribution to the CubeSat realm in two areas.

The physical work done at SSPL progresses the development of OSIRIS and OSIRIS-3U by
advancing one of its mission-enabling technologies that has, until this point, existed as only
a requirement. With the help of a history of prototypes and the documentation provided by
this thesis and other lab procedures makes it easy to pass this project on to incoming students,
maintaining the flow of education from one generation to the next.

The collection of knowledge attained from this project contributes to the CubeSat community
as a whole by drawing from the global pool of knowledge and then returning new findings to
the collective. This information, regardless of how it proceeds on OSIRIS, becomes publicly
accessible knowledge as it stands and will enable other CubeSat developers to possibly pursue
missions that may otherwise not be possible. Entities that possess the ability to perform research
and development may use this knowledge to kick start their process or to avoid some of the
mistakes made here. Engineering is a learning process, and the best way to truly utilize that
learned knowledge is to pass it on.

1.5 Overview

This thesis serves to document the process of developing the OSIRIS deployable boom system up
to this point; this process includes the application of principles learned both in the curriculum
at Penn State and through experience at the SSPL.

Chapter 1 provides an overview of the university CubeSat program and the OSIRIS mission
at Penn State that has been evolving over the last few years. It also presents the tools and
methods used in this work and also the relevance of the work. Chapter 2 examines OSIRIS in
greater detail to set the context for this project’s development.

Chapter 3 explores existing technologies and solutions that are relevant to this project in an
effort to understand the scope in which this project operates. The survey is broken into two
components: the general boom architecture and the release and latching mechanism used in the
device. Chapter 4 continues the engineering process by establishing baseline requirements upon
which this specific system is designed and then conceptualizing, down-selecting, and evolving
the design of the deployable boom system. Finally, the results of the project are presented in
Chapter 5 and the project conclusions and future work are discussed in Chapter 6.

¹RepRap printers at Penn State are funded by School of Engineering Design, Technology, and Professional
Programs (SEDTAPP) and built as part of the EDSGN 497C rapid prototyping class. They are maintained by
students and the State College RepRap Users Group.
Chapter 2

OSIRIS Baseline Design

The OSIRIS bus has been evolving since 2006, beginning with a simple design based on the Pumpkin CubeSat Kit.\(^1\) In 2010 and 2011, SSPL completed builds of OSIRIS Lite (OLite) and OSIRIS Lite 2 (OLite 2), respectively, and they are shown in Figure 2.1b. OLite and OLite 2 are high altitude balloon payloads intended for launch on the High Altitude Student Platform (HASP) balloon operated by Louisiana State University (LSU). The payloads were each an iteration of the OSIRIS architecture with the goal of increasing the TRL of selected hardware or risky technologies and of understanding the system as a whole.

The OLite 2 payload is partitioned into two sections: the CubeSat Simulator (CSS) and the support box. The CSS serves as a prototype of the OSIRIS bus, meeting the same form factor requirements as set forth in the CalPoly CubeSat Design Specification (CDS). While not all stringent CDS requirements are met by the prototype and some components, such as the science instruments, are excluded, the CSS provides a current baseline for the OSIRIS bus design. Thus, the deployable boom system is designed according to requirements derived from the CSS model which shall henceforth be referred to as OSIRIS.

2.1 Current Generation Satellite Bus

The OSIRIS bus is designed with efficient space utilization and also modularity due to the incremental development and substantial levels of testing required as the design progresses. As shown in Figure 2.2, the spacecraft is built around a skeletal structure using the solar panels as structural skin panels. The solar panels must include an indium tin oxide (ITO) –coated substrate to provide a ground return path for the science instrument, and the substrate is laminated to the solar panels to add structural rigidity and protect the solar cells. Subsystem and instrument circuit boards are slid into the structure and mated to a backplane board in a fashion similar to PCI boards and a motherboard in a personal computer. This allows easy integration and de-integration of the boards for testing and hardware updates. This design also lends to flexibility in mechanical design because the board spacing is not dependent upon inter-board header connections. Instead, the board slot positions and edge connectors on the backplane board can be repositioned between iterations to optimize internal volume usage. This design places a restriction on the deployable boom system, requiring it to occupy the volume between boards and thus needs to be relatively flat — less than approximately 2 centimeters thick — although the boards may be easily rearranged so the placement of the boom system is flexible.

The communication subsystem includes two crossed-dipole antennas on the +Z (nadir) face of the spacecraft, parallel to the face. Because of the nature of the antenna gain pattern, any

\(^1\)Pumpkin Incorporated sells CubeSat kits with many modular components. More information is available at http://www.cubesatkit.com/
Figure 2.1: CAD models of the HASP payloads
metallic secondary structures must be orthogonal to the antenna and not within close proximity relative to the spacecraft size. Regardless of material choice for the boom, the probe and cabling are still metallic and thus the boom is restricted to projecting orthogonally from the \(-Z\) (zenith) face.

### 2.2 The Hybrid Plasma Probe

The OSIRIS science mission, depending on configuration, will utilize three separate methods for measuring the effects of ionospheric plasma on RF propagation:

- GPS Radio Occultation (GPRSO) using a GPS module provided by Aerospace Corp. GPS signals are refracted through the atmosphere and differential phases in the signal are used to determine differential total electron content (TEC).

- An on-board beacon provided by the Naval Research Lab (NRL) transmits a signal that is received by ground based receivers. Delays in the signals are used to determine TEC between the satellite and ground.

- A probe on board the satellite collects \textit{in situ} measurements of the local plasma to determine electron temperature, electron density, and plasma electrical potential.

The final method uses a Hybrid Plasma Probe (HPP) developed at The Pennsylvania State University by students in SSPL and Systems Design Lab (SDL). The HPP is currently under development and many of its physical characteristics are not yet fully defined, but careful estimations are possible due to the research that has been completed thus far. The geometry of the probe is assumed to be that shown Figure 2.3, though the precise nature of the probe’s fixture and wiring interface are currently unknown.
The probe must be stowed inside of the CubeSat and deployed after ejection from the launch vehicle Poly-PicoSatellite Orbital Deployer (P-POD), thus requiring some type of deployable boom mechanism. The challenge stems from the science requirements for acceptable operation of the HPP. The OSIRIS satellite is certain to tumble in an arbitrary direction during its mission at a rate less than 10 degrees per second. The maximum anticipated spin rate is based on previous spacecraft launching from the same P-POD and models created by the guidance, navigation, and control (GNC) subsystem. When the satellite travels through the ionosphere, it will disturb the molecules and create a ram–wake sheath around the spacecraft, as shown in Figure 2.4, and data collected within the ram or wake is unusable.

The boom must be significantly long compared to the satellite in order to maximize the amount of data that is collected outside of the ram and wake. A longer booms translates into a higher percentage of usable data per rotation. The science subsystem has indicated that a length of 40 centimeters between the satellite center of mass (CoM) and the base of the HPP’s collector segment is sufficient. The goal is to at least meet this length requirement or exceed it if possible.

2.3 Development Schedule

The OSIRIS mission is slated to launch after 2012; this aggressive schedule necessitates a final version of the deployable boom system by late 2012 at the latest if the satellite is to launch on schedule. The deployable boom system is also applicable to the OSIRIS-3U mission currently proposed to NASA, and the schedule for OSIRIS-3U is presented in Figure 2.5.
Figure 2.5: Schedule for the OSIRIS-3U mission
Chapter 3

Survey of Previous and Current CubeSat Deployment Technologies

Large-scale deployable systems have been around for decades, often used on satellites and vehicles for erecting communication antennas and payload instrumentation that would otherwise not fit within the launch vehicle payload fairing. Most commercial-off-the-shelf (COTS) systems tend to be excessive in size relative to the CubeSat form factor, which leads to the necessity of developing an in-house system. Because the boom is only deployed once in flight and does not require retraction, the breadth of design possibilities is more open than if retraction were necessary.

3.1 Boom Architecture

Pellegrino, currently at Caltech, provides an overview of available boom and mast designs that have been employed in the last few decades, and the findings, along with internal comments, are summarized in Table 3.1 (Pellegrino, 1995, p. 1006–1008).

Tubular booms have accumulated considerable flight heritage — for example, Northrop Grumman’s storable tubular extendable member (STEM) system with “over 30 years of space flight heritage including programs such as Voyager, GPS IIR, Hubble Space Telescope, and Mars Pathfinder” (Northrop Grumman, nd). They also have considerable design flexibility in that they can be constructed with different cross sections to achieve different ends. A STEM design uses only one strip formed into a tube. A bi-STEM design reduces the necessary storage drum width and ploy region in the cassette by using two strips that fold into one another, also forming a tube. When high torsional strength is required, an interlocking STEM design “zippers” the STEM seam together or a collapsible tubular mast (CTM) design can be used where the boom uses a continuous cross section that can collapse. Some of the available cross sections are illustrated in Figure 3.1.

If the category of tubular booms is broadened to include open cross sectional members, then “tape measure” booms also become possible. This type of deployment uses an element similar or identical to the metallic measuring tape purchased at a hardware store. Tape measure deployments have some CubeSat heritage, either in demonstration or flight, with programs such as Montana EaRth-Orbiting Pico-Explorer (MEROPE) where they are used for antennas, and the Norwegian nCube where they used as a boom (George Hunyadi and Obland, nd). The nCube boom, shown in Figure 3.3 is of a similar nature to OSIRIS’s requirements when in a deployed state, but the nCube boom has a fixed root and deploys by unrolling from root to tip.
Table 3.1: Overview of deployable boom and mast design types

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Articulated</td>
<td>One or more tubular members are joined by motorized hinges. The hinges may also be made passive by elastic elements that are neutrally deployed and stowed loaded.</td>
</tr>
<tr>
<td>Tubular</td>
<td>The boom is constructed from a thin strip of metal, usually stainless steel or beryllium copper up to 0.2mm thick. The strip has a seam such that the tube can be flattened and stored on a drum. The drum and ploy region where the boom furls are contained within a cassette.</td>
</tr>
<tr>
<td>Telescoping</td>
<td>A boom or mast is constructed from two or more concentric sleeves that slide over one another. The boom or mast may be deployed by means of motorized mechanisms, spring mechanisms, or inflation. Telescoping booms do not appear to be very scalable at the CubeSat level.</td>
</tr>
<tr>
<td>Coilable</td>
<td>The boom or mast is built from wire or thin tube elements in a lattice, similar to large radio towers. In the case of Pellegrino’s research, the system is deployed by mechanical cables and motors, but the system may be scaled down by using shape memory alloys (SMAs) that can be stowed and then return to a programmed shape. An example is shown in Figure 3.2</td>
</tr>
</tbody>
</table>
and thus does not meet the OSIRIS requirements for the deployment process. This architecture is undesirable for OSIRIS since the boom tip holds the HPP, which could be easily damaged, and because the deployment must include a triaxial cable for the HPP operation.

![Diagram of deployable structure](image)

**Figure 3.2**: Example of a coilable mast used to deploy a solar array (Pellegrino, 1995, p. 1008)

### 3.2 Release and Latching Mechanism

Three main methods of locking the boom in its stowed state, releasing it, and latching it in the deployed state, if necessary, have been identified as relevant and plausible for this scale: pin pullers, burn wires, and magnetic actuators.

The first method involves a pin that locks an element in place relative to the surrounding structure. The pin is attached to a motor, magnetic actuator, or contracting material, such as SMA wire, that retracts the pin on command. The later type is shown in Figure 3.4. This mechanism has been used by SSPL on the ESPRIT rocket, but not at this small scale. COTS pin pullers are available, including the commonly used TiNi Aerospace models, but these solutions are much too large for this application (TiNi Aerospace, 2001). Of the three solutions, this is the only to use actively moving mechanical parts, increasing the risk for mechanical jamming and failure.

A more passive method is the burn wire mechanism, illustrated in Figure 3.5. The basic design includes a nylon monofilament line that holds the boom element in a stowed state, either by directly tying to points along the boom or by bounding the boom. The system is constructed in the stowed state and remains stowed until the point of deployment, at which point a heating element — usually a nichrome wire or similar — melts a point in the monofilament line, freeing the boom to deploy. This system is single-use and not resettable without replacing the monofilament.

The final small-scale solution is a magnetic release. The basic principle is illustrated in Figure 3.6. Ferrous tip masses are fixed to the end of the boom and to points along the boom,
Figure 3.3: Photo of nCube showing its tape measure deployment in the stowed configuration (Taken by Bjørn Pedersen, NTNU and released under the Creative Commons (cc-by) license)

Figure 3.4: Diagram of a basic pin puller mechanism using SMA wire

Figure 3.5: Diagram of a basic burn wire mechanism
if necessary. Each mass contacts a permanent magnetic core on the satellite, tying down the boom. To deploy, a solenoid coil around the magnetic core is activated, creating a magnetic field that cancels the permanent magnet and allows the boom to release. Heritage for this method is difficult to locate, and care must be taken with maintaining a clean magnetic environment for onboard instrumentation. This is especially critical for the magnetometer that is used for determining the spacecraft’s orientation while in orbit.

![Diagram of a basic magnetic release mechanism](image)

**Figure 3.6: Diagram of a basic magnetic release mechanism**

The locking and latching mechanism is not included in the initial trade studies for this development project because the implementation of the mechanism is highly dependent upon the form taken by the boom system. Certain types of boom systems may be inherently more adapted to certain locking mechanisms, or some may require a given locking mechanism for feasibility.
Chapter 4

OSIRIS Boom Development Process

The boom development process is a largely exploratory and fast paced one. Basic requirements are well understood, and the rapidly evolving requirements internal to other subsystems of OSIRIS do not, for the most part, have a substantial impact on the boom system. The issues to be solved are almost purely with operation of the mechanisms themselves. Taking advantage of the RepRap 3D printers that are available to this project, a spiral development model is used to quickly resolve requirements, design and prototype, and address and solve design problems. An example of the spiral development model is provided in Figure 4.1.

4.1 Requirements Definition

The OSIRIS boom development team has generated design requirements based upon research of the OSIRIS objectives, examination of the CalPoly CDS, and discussion with leads of the other OSIRIS subsystems and the systems engineer. The requirements are listed in Table 4.1, and the complete OSIRIS requirements documentation is available from the SSPL OSIRIS document library as document title Boom Design Requirements.

The HPP generates the science driven requirements. As the HPP is the reason for including a boom, these requirements cannot be negotiated from existence, but the measurements in these requirements will evolve as the HPP is developed. For example, the tip mass is currently estimated until the probe reaches a refined design stage.

4.2 Initial Conceptualization and Trade Study

The historical boom technologies presented in Chapter 3 are combined with additional research in specific design variables, including technologies that are similar and applicable such as deployable antenna technologies, and summarized in a mind map in Appendix A. The boom architecture manifests itself in the form of two variables, boom type and boom placement and packaging. The material is also a design variable but will be investigated further with testing and development and does not have a substantial impact on the architecture trade study. Electrical isolation assurance plays a role in considering the validity of different design concepts. The latching or deployment mechanism will be examined in a further trade study, but it is considered in the initial conceptualization phase to assure that the chosen concept is plausible for incorporating one of the possible mechanisms.
Figure 4.1: Example of the spiral development model (adapted from Boehm, 1988)
Table 4.1: OSIRIS boom design requirements

<table>
<thead>
<tr>
<th>Req. No.</th>
<th>Requirement Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Science Driven Requirements</strong></td>
<td></td>
</tr>
<tr>
<td>20-01</td>
<td>The boom shall support a tip mass of 30 g.</td>
</tr>
<tr>
<td>20-02</td>
<td>The system shall be capable of storing a probe of dimensions shown in Figure 2.3.</td>
</tr>
<tr>
<td>20-03</td>
<td>The boom shall provide a separation of at least 0.400 meters between the satellite bus CoM and base of the HPP collector with a goal of up to 1.000-meter separation.</td>
</tr>
<tr>
<td><strong>Mechanical Requirements</strong></td>
<td></td>
</tr>
<tr>
<td>30-01</td>
<td>The boom shall deflect no more than TBD meters laterally at the probe’s CoM.</td>
</tr>
<tr>
<td>30-02</td>
<td>The boom shall be linearly rigid such that the length does not vary by more than TBD between the CubeSat bus and the HPP.</td>
</tr>
<tr>
<td>30-03</td>
<td>All materials used in the deployment system shall have an outgassing total mass loss (TML) of less than 1.0%.</td>
</tr>
<tr>
<td>30-04</td>
<td>The deployment system shall withstand random vibrations as specified by GSFC-STD-7000.</td>
</tr>
<tr>
<td>30-05</td>
<td>The boom shall be perpendicular to the plane created by the communication subsystem (COM) antennas.</td>
</tr>
<tr>
<td><strong>Stowage</strong></td>
<td></td>
</tr>
<tr>
<td>31-01</td>
<td>When the HPP is stowed, no part of the boom or probe shall extend outside of the enveloped specified by the CalPoly CDS.</td>
</tr>
<tr>
<td>31-02</td>
<td>The HPP shall be protected against scratching, marring, or otherwise damaging contact or vibration against metal surfaces when stowed.</td>
</tr>
<tr>
<td>31-03</td>
<td>Deployable components shall be stowed and constrained entirely by the CubeSat such that they do not contact the P-POD or use the P-POD as a mechanism for containment.</td>
</tr>
<tr>
<td><strong>Deployment</strong></td>
<td></td>
</tr>
<tr>
<td>32-01</td>
<td>The deployment process must occur autonomously once the CubeSat system triggers the deployment event.</td>
</tr>
<tr>
<td>32-02</td>
<td>Sensor feedback shall be sent to command and data handling subsystem (CDH) that indicates the current state of the deployable boom system, i.e., stowed, in transit, or deployed.</td>
</tr>
<tr>
<td>32-03</td>
<td>All parts shall remain attached to the CubeSat during and after deployment. No additional debris shall be created.</td>
</tr>
<tr>
<td>32-04</td>
<td>Pyrotechnics shall not be permitted.</td>
</tr>
<tr>
<td><strong>Electrical Requirements</strong></td>
<td></td>
</tr>
<tr>
<td>40-01</td>
<td>The boom shall accommodate a 50-ohm characteristic impedance cable from root to tip. TBR</td>
</tr>
<tr>
<td>40-02</td>
<td>The deployment shall consume less than 4 watt-hours from stowed state to deployed state.</td>
</tr>
<tr>
<td>40-03</td>
<td>The deployment shall draw less than 10-amp peak.</td>
</tr>
<tr>
<td>40-04</td>
<td>The deployment system shall have a single point ground to the chassis.</td>
</tr>
<tr>
<td>40-05</td>
<td>The exterior surface of the boom shall be non-conductive.</td>
</tr>
<tr>
<td><strong>Development Requirements</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Testing</strong></td>
<td></td>
</tr>
<tr>
<td>51-01</td>
<td>The boom shall be in a configuration that allows for repeated testing of prototype and flight units with a reset time of less than five hours.</td>
</tr>
</tbody>
</table>
Concepts were generated by laying out the possible design components and selecting plausible combinations of options that promise the most compatibility among options. For example, an internally stowed articulated boom is not feasible. The selected design concepts are shown in Figure 4.2.

Analysis of these five options from an objective standpoint requires a numerical trade study that attempts to minimize bias in the selection process. To achieve this end, the OSIRIS boom development team developed metrics by which the concepts are measured, relative weights for those metrics, and finally scored the concepts. For each part of this process, all subsystem leads and members were invited to attend a session such that a broad cross section of all stakeholders and areas of expertise could be sampled.

Upon examination of the requirements listed in Table 4.1 and deliberation with the project subsystems, a set of metrics was produced that encompasses the key areas of interest for the boom’s function, performance, and risk minimization. The metrics are presented and described in Table 4.2.
### Table 4.2: OSIRIS boom concept metrics

<table>
<thead>
<tr>
<th>Metric Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Volume Usage</td>
<td>Volume is highly restricted in the CubeSat. Less volume used and higher density is better.</td>
</tr>
<tr>
<td>Mass</td>
<td>The CubeSat is restricted to 1.33 kg, so mass is a factor; however, OSIRIS currently has a high mass margin.</td>
</tr>
<tr>
<td>Reliability of Deployment</td>
<td>The deployment must deploy with complete confidence for science to be successful.</td>
</tr>
<tr>
<td>Cost</td>
<td>CubeSats are intended to be low cost, and the boom may be expensive to develop.</td>
</tr>
<tr>
<td>Ease of Manufacturing</td>
<td>If possible, all parts should be producible in house in order to maximize student involvement and learning.</td>
</tr>
<tr>
<td>Rigidity</td>
<td>Good science data depends on knowing the probe location so that ram–wake data can be filtered, and large flexing or variance in the boom resulting during deployment may compromise the data fidelity. Once deployed, minimal loading will be placed on the boom.</td>
</tr>
<tr>
<td>Ease of Testing</td>
<td>Students will be testing the boom in house to facilitate rapid revisions and quality assurance.</td>
</tr>
<tr>
<td>Heat Generation</td>
<td>Some systems may produce heat, which may have negative implications for the bus.</td>
</tr>
<tr>
<td>Deployment Time</td>
<td>Deployment time is an open-ended requirement, but for the purposes of a realistic system, a lower deployment time is better.</td>
</tr>
<tr>
<td>Total Electrical Energy Consumption</td>
<td>Over the course of the satellite’s lifetime, a low continuous electrical energy consumption is preferable to minimize drain on the reserve batteries.</td>
</tr>
<tr>
<td>Risk of Satellite Damage</td>
<td>Depending on the deployment architecture, adverse behavior may cause damage to the ITO coatings or internal components.</td>
</tr>
<tr>
<td>Thermal Effects on Deployment</td>
<td>The temperature of the boom system may not be highly controllable, so the boom should be capable of deployment over a wide range of temperatures expected on orbit.</td>
</tr>
<tr>
<td>Design Impact on Panels, Sensors, etc.</td>
<td>Solar panel real estate is at a premium and major impacts, such as removing solar cells or repositioning sun sensors, could jeopardize the satellite design.</td>
</tr>
<tr>
<td>Antenna Interference</td>
<td>The boom must be orthogonal to the antennas to minimize interference, but booms with inordinate amounts of metal or protrusion could affect the antenna gain pattern.</td>
</tr>
<tr>
<td>Number of Components</td>
<td>A higher number of components is generally correlated to a higher level of complexity and longer manufacturing time and difficulty.</td>
</tr>
<tr>
<td>Number of Failure Points</td>
<td>Minimizing the number of possible failure points and modes also minimizes the failure risk.</td>
</tr>
<tr>
<td>Impact of Failure</td>
<td>A deployment failure will always compromise science, but it could also prevent beaconing or transmitting or receiving data, depending on the failure mode.</td>
</tr>
<tr>
<td>Ease of HPP Mounting</td>
<td>The HPP is still under development, so the boom should be as least restrictive to mounting methods as possible.</td>
</tr>
<tr>
<td>Peak Power Consumption</td>
<td>The power available per orbit is limited, so the boom should not drain the satellite’s power reserves during deployment.</td>
</tr>
<tr>
<td>Robustness while Stowed</td>
<td>The launch environment will be violent, so the boom must tolerate high levels of vibration without damage to itself or the attached HPP.</td>
</tr>
</tbody>
</table>
The metrics are not of equal importance in the scope of the project, so they are each compared to the other metrics and the relative importance of each is determined in a pairwise comparison matrix. A detailed view of the matrix and score summary is presented in Figure B.1 in Appendix B, and a brief summary of the scores is presented here in Table 4.3.

Table 4.3: Metric score summary

<table>
<thead>
<tr>
<th>Metric Name</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Volume Usage</td>
<td>0.058</td>
</tr>
<tr>
<td>Mass</td>
<td>0.046</td>
</tr>
<tr>
<td>Reliability of Deployment</td>
<td>0.064</td>
</tr>
<tr>
<td>Cost</td>
<td>0.033</td>
</tr>
<tr>
<td>Ease of Manufacturing</td>
<td>0.041</td>
</tr>
<tr>
<td>Rigidity</td>
<td>0.061</td>
</tr>
<tr>
<td>Ease of Testing</td>
<td>0.043</td>
</tr>
<tr>
<td>Heat Generation</td>
<td>0.037</td>
</tr>
<tr>
<td>Deployment Time</td>
<td>0.034</td>
</tr>
<tr>
<td>Total Electrical Energy Consumption</td>
<td>0.051</td>
</tr>
<tr>
<td>Risk of Satellite Damage</td>
<td>0.061</td>
</tr>
<tr>
<td>Thermal Effects on Deployment</td>
<td>0.039</td>
</tr>
<tr>
<td>Design Impact on Panels, Sensors, etc.</td>
<td>0.064</td>
</tr>
<tr>
<td>Antenna Interference</td>
<td>0.061</td>
</tr>
<tr>
<td>Number of Components</td>
<td>0.042</td>
</tr>
<tr>
<td>Number of Failure Points</td>
<td>0.064</td>
</tr>
<tr>
<td>Impact of Failure</td>
<td>0.064</td>
</tr>
<tr>
<td>Ease of HPP Mounting</td>
<td>0.037</td>
</tr>
<tr>
<td>Peak Power Consumption</td>
<td>0.047</td>
</tr>
<tr>
<td>Robustness while Stowed</td>
<td>0.055</td>
</tr>
</tbody>
</table>

These weights are used in the Pugh matrix, shown in Figure B.2 of Appendix B. With available persons at SSPL present, each metric for each design option was deliberated until a consensus was reached. The process consumes considerably more time than a “gut feeling” decision, but the result is significantly less subjective than that of other methods.

Table 4.4: Concept scores

<table>
<thead>
<tr>
<th>Concept Description</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tape measure with parallel triax stowed on internal cassette</td>
<td>3.840</td>
</tr>
<tr>
<td>Tape measure with parallel triax cable stowed around spacecraft</td>
<td>3.803</td>
</tr>
<tr>
<td>CTM formed as triax stowed on internal drum</td>
<td>3.653</td>
</tr>
<tr>
<td>Telescoping boom recessed into one side with parallel triax</td>
<td>3.746</td>
</tr>
<tr>
<td>SMA recessed into one side with parallel triax</td>
<td>3.422</td>
</tr>
</tbody>
</table>

While all concepts in Table 4.4 score between 3 and 4, this is expected with such a large number of metrics since minor variations in individual scorings will average out in the summation. The differences in score, however, are strong enough to suggest against those that score poorly. Discussion with stakeholder members on the project confirmed the low feasibility of the low-scoring concepts on this project, and thus further analysis of the scores was not deemed necessary; however, application of this study to future projects may warrant additional analysis. The two highest scoring concepts are similar enough that both are worth examining further to determine
if they warrant serious pursuing. The results are also consistent with recommendations from professional engineers with experience on similar systems.\textsuperscript{1}

Initial CAD models of the externally stowed, or wraparound, concept are not promising. Shown in 4.3, the design is not as simple as expected. For reference, the guard plate, shown in light blue, is 112-mm wide. The boom needs a guide way for stowage so that it cannot freely move about the outside of the satellite and so that it cannot potentially damage the ITO coatings. The probe must be recessed beneath the surface of the solar panels, leading to the pocket along the left side of the design.

![Figure 4.3: CAD model of the externally stowed boom concept](image)

If this model could be included in the satellite parallel to the Z faces, then the boards could still slide into the structure with only a modification to their clearances where the boom guide way is located. This however, is not possible. The antennas must be located on and parallel to the $+Z$ face in order to achieve the desired gain patterns, which leads to a requirement on the boom’s location on and normal to the $-Z$ face. Such a configuration is not possible if the guide way were to wrap around parallel to the Z faces.

With this realization, the externally stowed design, which was initially the default, is set aside due to the complexities and interface issues that face it. Therefore, the internally stowed design is pursued in the detailed design phase.

\textsuperscript{1}David J. Rohweller, the Principal Mechanical Technologist at Northrop Grumman Aerospace Systems recommended in a personal email correspondence that, for our scale, a simple arc tape measure such as that found at a hardware store would be sufficient for our needs.
4.3 Detailed Design

Detailed design of the OSIRIS deployable boom system followed description of the general design and selection of specific components to be used in the design. The design is described as follows:

- Open arc tape measure boom element.
- Boom stowed internally in a self-contained cassette.
- Triax cable is run parallel to the boom.
- Boom deployment is assisted by a constant force spring.
- Boom is retained in its stowed state by a pin through the boom element.
- HPP is stowed in a protective sleeve as part of the deployment cassette.

Two major components needed selecting prior to drafting the first design version: the deployment assist springs and the tape measure boom element, which henceforth shall be referred to as the “tape.” The selected constant force springs selected are listed in Table 4.5. Note that all springs have a life of 4,000 cycles. The tape is taken from a measuring tape purchased from a hardware store. It is a 0.5-inch wide tape, and Figure 4.4 shows the tape attached to the 1.62 lbs spring.

For each of the prototypes, each of the four springs is tested to determine if a larger or smaller force has any significant impact on the design performance. In all cases, photos of prototypes include the 1.62-lbs spring.

<table>
<thead>
<tr>
<th>Load Force (lbs.)</th>
<th>Wound OD (in.)</th>
<th>Wound ID (in.)</th>
<th>Width (in.)</th>
<th>Thickness (in.)</th>
<th>McMaster Part No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.66</td>
<td>0.40</td>
<td>0.28</td>
<td>0.25</td>
<td>0.004</td>
<td>9293K42</td>
</tr>
<tr>
<td>1.03</td>
<td>0.50</td>
<td>0.37</td>
<td>0.312</td>
<td>0.005</td>
<td>9293K44</td>
</tr>
<tr>
<td>1.12</td>
<td>0.62</td>
<td>0.51</td>
<td>0.37</td>
<td>0.006</td>
<td>9293K46</td>
</tr>
<tr>
<td>1.62</td>
<td>0.75</td>
<td>0.59</td>
<td>0.50</td>
<td>0.007</td>
<td>9293K48</td>
</tr>
</tbody>
</table>

The first version of the design assumes that the boom and the triax cable can be stowed on a common spool that will feed both from the cassette simultaneously. It also assumes that the boom’s tendency to expand on the spool will generate sufficient friction to prevent deployment, and this issue is resolved by including a filament between layers of the boom on its spool that is drawn by the assist spring. In this design, the boom is “pulled” from the spool instead of “pushed,” preventing it from expanding while stowed. An illustration of this concept is shown in Figure 4.5, and the CAD model of version 1 is shown in Figure 4.6.

The overall size of the cassette for version 1 is approximately 4 × 4 × 5 centimeters without including the HPP housing, and this is too large for accommodation in OSIRIS. After adjusting the model, this size cannot be decreased to an acceptable size because of the way in which the mechanisms function.

The next version discontinues the separate filament for deployment and condenses the mechanisms into a single, fixed spindle. The design carries a higher risk of the boom binding if it expands inside of the cassette, but the form factor is much smaller. Instead of a separate spindle pulling the boom from its stowage spindle, the boom is fixed directly to the constant force spring which ejects the boom from its housing. The CAD model, shown in Figure includes the HPP housing, though it does not include the triax cable. While this design is large on the scale of the CubeSat when including the HPP, the width and height of the package are small enough.
Figure 4.4: Boom tape attached to 1.62-lbs spring

Figure 4.5: Illustration of the deployment concept for design version 1
that it may fit in the clearance between a circuit board and solar panel if the proper electronic component clearances are maintained.

4.4 Prototypes and Revisions

The OSIRIS deployable boom cassette is prototyped using polylactic acid (PLA) plastic and the RepRap printers built by students at Penn State. The first prototype is an exact build of the design in Figure 4.8, and is shown in Figure 4.9.

This first prototype immediately revealed a major design flaw with this first iteration that needed correction before continuing. While the spindle and cassette housing were sized correctly for the spring, the cassette was sized too small for the tape. The tape’s minimum bend radius was slightly smaller than that of the cassette’s pocket, preventing the tape from being coiled inside.

The next iteration features a pocket that is 0.25 inches in diameter larger to accommodate the tape. The second prototype is shown in Figure 4.10 with the spring and tape. This iteration showed the tape is easily accommodated by the size of the cassette; however, high levels of friction prevent the tape from being loaded externally by pushing the boom into the cassette and prevent the boom from easily deploying when released. The cassette and boom were sprayed with Aerodag G graphite coating to help alleviate the friction, but the tape still binded during retraction.

The remaining prototypes attempt to address the friction problem by scaling up the cassette and including additional hardware that is readily available. The second prototype in Figure 4.10 is the target cassette size for the flight version, and it is assumed that solutions implemented in additional prototypes may be scaled down to meet the target package.

Drawings of the baseline cassette package are found in Appendix C.

The third prototype attempts to address the friction problem by adding ball roller bearings at four points around the cassette. The prototype is shown in Figure 4.11. The bearings demonstrate a substantial improvement upon the previous version. The tape still resists and binds when the boom is forcefully loaded by pushing it in from the outside, at which point the circular loading deforms and fills the shape of the pocket, as visible in Figure 4.11d. Also, the constant force
Figure 4.7: Exploded view render of the current version of the OSIRIS deployable boom

Figure 4.8: Render of the current version of the OSIRIS deployable boom
Figure 4.9: First prototype iteration of the OSIRIS deployment cassette
Figure 4.10: Second prototype iteration of the OSIRIS deployment cassette sprayed with Aerodag G
spring tends to shift to one side when loaded, causing additional friction on that side of the cassette.

The fourth prototype attempts to address the deformation issues by using closely spaced rollers around the perimeter of the boom stowage pocket. The solution is inspired by the University of Hawaii Nanosat’s preliminary tether mechanism design, shown in Figure 4.12 (Yoneshige, nd, p. 40). The University of Hawaii encountered friction errors within the rollers and abandoned the design without troubleshooting in favor of folding the boom into the satellite; however, this alternative method has a higher volume requirement, as admitted by the designers, and thus is not feasible for OSIRIS.

The fourth prototype using nylon rollers is shown in Figure 4.13. When the tape is only partially retracted by external force, it rolls easily inside of the rollers; however, as the tape is loaded beyond approximately 10 centimeters, the tape begins to bind on itself and deforms in the region where it exits the cassette, as visible in Figure 4.13d. Lubrication on the rollers has no noticeable effect on the boom’s functionality since the boom is binding on itself and not on the rollers. The same boom tape with Aerodag G graphite coating is used in this prototype.

4.4.1 Addressing the Friction Problem

In the later prototypes involving ball and roller bearings, the consensus among involved student engineers based on observation is that friction within the tape itself, and not against the outside wall, is the cause for binding. Some resistance is also caused by the deformation of the tape’s coiled shape, preventing smooth motion within the cassette. The tape is painted, though surface finish is ruled out as a major factor due to the lack of effect by the Aerodag G coating; other coatings, however, may be investigated to reduce friction from wear.

The cause for the high levels of friction are, upon investigation, due to the spring assist inside of the cassette. As the tape is externally loaded by pushing it into the cassette, the spring causes the layers of the tape coil to wind more tightly against one another than they would normally. Upon deploying, the spring causes the layers of the coil to want to all uncoil simultaneously instead of from the outside in, and the attempts to reduce friction around the perimeter are not sufficient to overcome this problem. The result is that the tape binds upon itself, and this theory is confirmed by removing the spring and repeating loading and deploying tests. The nature of the tests have been to either yield no motion at all or to yield smooth motion, and thus quantitative measurements have not yet been meaningful. The qualitative results are confirmed using the third prototype with ball bearings. Future iterations may include modified roller bearings to accomplish the same ends but with more effective volume usage.

4.4.2 Triax Cable Stowage

Three methods for stowing the triax cable have been investigated, evolving the method for stowage as the properties of the triax became more well understood. The triax cable for the HPP is not readily available and difficult to acquire, but a sample of appropriate cable is available from a previous SDL project developing a Langmuir probe. The triax cable sample is shown in Figure 4.14, though the sample does not include a supplier or part number, and thus the manufacturer rated technical specifications are unknown. Throughout the testing process, those involved rely upon previous experience with similar cabling to gauge the reasonable mechanical limits of the sample.

In an effort to minimize volume usage, the initial stowage concept was to coil the cable in a helix around the HPP housing shown in Figure 4.7 and 4.8. Unfortunately, upon acquisition of the cable sample, the bend radius of the cable before it offers significant resistance is much larger than necessary for effective coiling about the HPP housing.

The second concept is the fire-hose storage case. The cassette includes an integrated pocket along the back surface formed from two plates of 3-inch by 3.5-inch separated by approximately
Figure 4.11: Third prototype iteration of the OSIRIS deployment cassette to demonstrate ball roller bearings
0.25-inches to accommodate the cable diameter, shown in Figure 4.15. The cable is then folded into the pocket, and upon deployment the boom extracts the cable as it extends. The cable can comfortably bend to slightly over 0.5-inch diameter, allowing stowage of 58-centimeters of cable if loaded loosely as shown in Figure 4.16a, and this result provides enough cable to meet the minimum requirement of approximately 40 centimeters. If the cable is forced to a slightly tighter bending radius, which should not damage the cable when only stored in this manner one time, the unit stows 68-centimeters of cable, shown in Figure 4.16b; however, upon extraction of the cable from this state, some deformation is observed in the cable (see Figure 4.17) though this deformation is easily removed with light tension. Whether or not the boom can remove that deformation during deployment is speculative pending testing in relevant environments, and a method that does not include this problem would be desirable.

In an effort to further reduce volume usage and in consideration of the OSIRIS-3U satellite in which the panel containing the boom cannot be used for solar area, a third solution is devised in which the cable is coiled flat against the outside panel through which the boom ejects. While this concept has not been extensively prototyped, the general concept has been examined using the available triax sample. It is found that the cable is pliable enough for easy coiling into the desired shape, and when extracted linearly perpendicular to the surface, it is able to absorb any axial twisting that occurs in the cable. When the cable is cooled to 0 °C, the bend radius is not noticeably affected, though the cable does appear to lose some pliability, warranting further thermal testing. Thus, this configuration may be a viable option in triax stowing, but the previous fire-hose storage option is also available as a promising fall back.
Figure 4.13: Fourth prototype iteration of the OSIRIS deployment cassette with nylon rollers
Figure 4.14: Triax cable sample

(a) Top view

(b) Exit view

Figure 4.15: Fire-hose storage case for the triax cable
Figure 4.16: Initial attempts at loading the fire-hose storage case with triax cable

(a) Loose bending radius

(b) Tight bending radius

Figure 4.17: Deformation of the triax cable post-stowage with a tight bending radius
Figure 4.18: Triax panel coil concept

- Triax Cable
- Boom
- Boom and HPP Exit
- Skin Panel or Solar Panel
Chapter 5

Results of the OSIRIS Boom Development

The results of this development project at this time of this document’s authoring is a working concept with basic prototype that serves to increase the TRL of the component and lays a solid foundation for continued development of the deployment system for eventual inclusion in the OSIRIS and OSIRIS-3U spacecraft.

Until this point, a NanoSat scale deployment system of this capability has not been observed in practical application, leaving this project to begin from fundamental stages. Thus, this system began with an estimated TRL of 2, and in a relatively short time it has risen to a TRL 3 and is on the brink of becoming TRL 4 with a complete prototype. Any advancement beyond TRL 4 will require substantial environmental simulations and flight demonstrations on future high altitude balloons.

The current prototypes are not complete functional models; however, they serve as promising proof-of-concepts and illustrate the plausibility of a deployment of this type at the NanoSat scale — something which has not yet been accomplished and made public to the NanoSat community. From this point, a solid design can progress quickly through prototype, verification and validation, testing, and inclusion in the flight model of the spacecraft.

5.1 Current Revision Design of the Boom

The current revision of the OSIRIS deployable boom system is a culmination of the evolution of the deployment cassette, lessons learned from each prototype, and careful consideration of the triax stowage to minimize impact on the spacecraft. The current revision is shown in Figure 5.1.

The cassette is a standalone unit that handles stowage and deployment of the boom tape and stowage of the HPP prior to deployment. The form factor is that of the version shown in Figure 4.8, but the cassette includes a smaller version of the bearings used in the third prototype pictured in Figure 4.11. The entire cassette is machined from aluminum, and the HPP housing includes an elastomer material lining to protect the HPP. Drawings of the cassette without the ball bearings are shown in Appendix C.

The cassette mounts in two locations. Because of its proximity to the solar or skin panel, the HPP housing bolts directly to this panel in order to maintain correct alignment with the exit opening and prevent snagging. Because of the cassette’s mass, it must also be mounted to the structural frame to prevent movement and damage during launch. The exact placement of the cassette within the spacecraft bus is not yet determined, so fixtures will be added to the cassette at appropriate locations in the future when the placement is known with greater accuracy.
Figure 5.1: Current design of the OSIRIS deployable boom system
To maintain correct orientation of the boom, a guide is included in the cassette at the tape’s egress point. The guide, shown in Figure 4.7 and in greater detail on page 53 of Appendix 2.4. The guide serves to maintain orthogonality between the boom and the egress skin panel by providing a pathway that is the exact shape of the boom tape. This guide is machined from Delrin to achieve a low friction path.

The mechanism that secures the boom and deploys it after launch is not yet incorporated in detail within the CAD design, but given the nature of the device a burn wire or pin puller are the most promising solutions, though both would be implemented in the same manner and require additional prototyping to determine which is optimal. Because of the nature of the boom tape stowage, securing the boom outside of the coiled region is not ideal as this would further exacerbate the binding issue. Instead, the coiled tape needs to be rooted to a drum, and that drum is secured by either a pin or a wrapped burn wire.

The triax is looped around the surface of the egress skin panel while stowed. To achieve the minimum 40-centimeter boom length, two loops of triax are necessary. The triax is guided by four protrusions from the skin panel, and it is fixed against the panel by four burn wires. When the boom is deployed, the HPP will pull the triax cable from the panel.

The method for securing the boom tape and triax cable to the HPP are not currently certain as the HPP is under development. It is assumed that a plastic fixture can be extruded from the base of the HPP to which the boom tape and triax may be rooted. This interface must be coordinated between the mechanical subsystem and the HPP development group.

5.2 Testing of the Deployment System and Mechanisms

Current testing of the OSIRIS deployable boom system consists of bench tests using the RepRap-produced prototypes in order to gauge the functionality of various design revisions. The testing did not reach an environmental stage as testing was focused on pinpointing potential functional flaws at each stage and addressing them in new design iterations. The parts used, however, were representative of what will be used in the flight version.

The testing up to this point has focused on two key elements that posed the greatest uncertainty: the spring-tape system and the triax cable.

Testing of the spring-tape system was executed through the various prototypes of the cassette, into each of which the tape was loaded using each of the springs discussed in Table 4.5. The expectation was for a key spring size to perform well, while the others would either not have the force necessary for deployment or to exert too much force and deploy violently. Of course, the result was unexpected and the entire system binded during deployment, causing the assist spring to be reevaluated as a necessary component.

The triax cable, because of the difficulty in locating a supplier or technical specifications for the existing sample, can only be evaluated at this time through testing and observation. Repeated flexing of the cable and comparison to the resistance of similar cables at their minimum bend radius has given us an estimate of the triax bend radius. Repeated flexing has also shown that the cable’s insulator is prone to slipping along the cable’s length on the order of several millimeters over a 3-foot length, and thus when the cable is included in flight designs, the cable’s insulator must be physically secured by some type of ferrule to prevent unintentional exposure of the outer conductor.

5.3 Integration with the OSIRIS Satellite Bus

Developing the system within SolidWorks 3D CAD has allowed smooth integration planning with the OSIRIS bus, which is also designed in SolidWorks. With each new iteration of the design, the deployable boom system design team has worked closely with the mechanical subsystem group.
charged with maintaining the OSIRIS physical model. The current design version is smaller than the width of one circuit board slot in the bus and can be accommodated within the bus by adjusting the existing circuit board spacing.

The boom system will require modification to some subsystems in the spacecraft. The \(-Z\) solar panel will include an opening for the boom and HPP exit of approximately 2 centimeters in diameter, which also means that two solar cells must be removed. If the coiled triax stowage concept is employed, further modification to the solar panel is necessary, but solar cells may be preserved. Inside the spacecraft, circuit boards must be repositioned but removal of circuit boards is not necessary. Board component clearances, however, will be affected and board layouts may need adjusted accordingly.
Chapter 6

Conclusions and Future Work

CubeSats are becoming a crucial component in university research and other lower-budget, science-dense missions and are quickly changing the future of accessibility to space. So far, technologies have been developed with each new mission, attempting to scale the capabilities of macro satellites to centimeter scales. In this case, OSIRIS requires a deploying boom capable of delivering a probe to 40 centimeters or more from the spacecraft.

Through the work thus far in the OSIRIS deployable boom system development project, the team has demonstrated the feasibility of a nanosat-scale unit that can achieve the desired goals. The final design has not yet been perfected and manufactured for environmental and flight testing, but functional rapid prototypes have demonstrated a proof-of-concept that demonstrates basic functionality at near the desired size. Through continued work, the unit can be designed to be hard against launch and operational environments, to include the HPP appropriately as it is developed, to decrease further in size, to be adapted to interface with the OSIRIS structural bus, and to employ appropriate stowage and release mechanisms with a high degree of reliability.

This technology, upon demonstration both in prototype and flight on OSIRIS and/or OSIRIS-3U will be a valuable addition to the selection of CubeSat technologies already available in the nanosat community. As an SSPL project, the technology is viewed as a resource to further the development of CubeSats as a whole and will add to the missions that universities and small organizations are capable of supporting.

This thesis demonstrates the process by which the OSIRIS deployable boom system has evolved thus far to reach its current point. Applying engineering design principles and systems engineering concepts, the deployable boom system has increased considerably in TRL while also maintaining compatibility with the rest of the OSIRIS system, preventing major issues in the future when the unit is integrated.

The general principles for this design are understood and the design exists as a model ready for a full demonstration, though the new mechanism has not yet been prototyped. The next step is to construct a prototype with the new deployment mechanism without an assist spring and perimeter ball bearings to demonstrate its functionality. Then it is necessary to create this design to its full extent as a physical prototype that includes all components, including a mock-up of the skin or solar panel to which it is interfaced, and demonstrate full functionality of the completed system. This prototype should be fabricated in a manner similar to that expected for the flight model.

Not only will this final prototype be useful in demonstrating the deployable boom system’s function, but it will also be useful in environmental testing to determine the operational limits of the system. Such testing is vital to ensure reliable operation in the space environment and, if necessary, to determine what thermal sensors and controls need to be included with the unit when installed. Environmental testing will include two parts. First, the system will undergo a series of thermal–vac tests in the SSPL vacuum chamber facility to test the response to thermal
variations in a low pressure environment. Second, the system will undergo vibration testing to ensure the system is resilient to launch vehicle environments and that it will not fail.

In parallel, the OSIRIS mechanical subsystem will be working with the deployable boom system development team to create the interfaces between the boom system and the satellite bus and to address partitioning within the spacecraft to accommodate the boom system’s volume and adjust board clearances and keep-out areas as necessary. This step is the precursor to creation of an OSIRIS prototype that includes the deployable boom system — something that has not yet been accomplished in the OSIRIS history. Thus far, all satellite prototypes have neglected the boom because it had not yet been developed to a satisfactory point at which it could be included with any certainty as to its form.

Inclusion of the deployable boom system in the OSIRIS bus will disturb many of the system’s mechanical parameters, including mass and CoM. The mass budget is expected to absorb the additional mass without any significant problem. The CoM shift, however, may pose a challenge, as the CalPoly CDS places strict requirements on the CoM location. Thus, repartitioning and relocating components within the spacecraft may be necessary.
Appendix A

Design Variables

The following page contains a mind map of the design variables in consideration for generating concepts of the OSIRIS deployable boom system.
Figure A.1: Design variables and options considered in the initial concept generation phase.
Appendix B

Trade Study Matrices

The following two pages contain the matrices used in processing the OSIRIS boom architecture through a trade study in order to determine the best option or options to pursue in development.
Figure B.1: Pairwise comparison matrix of the boom architecture decision metrics with a maximum score of 2.
Figure B.2: Pugh matrix of the boom architecture decision metrics with a maximum score of 5.

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Final Score: 3.803, 3.840, 3.653, 3.422, 3.746
Appendix C

Baseline Design Drawings

The following pages contain the 3D CAD part and assembly drawings for the OSIRIS deployable boom system baseline as of November 4, 2011 which reflect the target package of the deployment cassette.
OSIRIS Boom Development

STRUCTURES SUBSYSTEM

8201-03-XXXX
MASTER DRAWING SET
GLOBAL REVISION 003

4 November 2011
CASSETTE COVER PLATE

DIMENSIONS ARE IN INCHES
TOLERANCES:

FRACTIONAL

ANGULAR:
MACH 1
BEND 1

TWO PLACE DECIMAL .005
THREE PLACE DECIMAL .0005

INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M

MATERIAL FINISH
6061-T6 ALUMINUM

SCALE: 3:1
UNLESS OTHERWISE SPECIFIED:
SHEET 4 OF 7
8201-03-XXXX
DO NOT SCALE DRAWING

R.250
R.050
.283
1.575
.125
.675
1.225
3X
.096 THRU ALL
1.700
1.350
1.450

NOTE: ALL

8.000
8.250
2.83
1.200
1.375
1.575
2.025
1.400

NOTE: ALL

51
**PROBE SLEEVE**

Dimensions are in inches

- TOLERANCES:
  - FRACTIONAL: .05
  - ANGULAR: MACH 1 BEND 1
  - TWO PLACE DECIMAL: .005
  - THREE PLACE DECIMAL: .0005

Interpret geometric tolerancing per: ANSI Y14.5M

Material: 6061-T6 ALUMINUM

Part may be split for 3D printed prototype

**NOTES:**
- DO NOT SCALE DRAWING
- PART MAY BE SPLIT FOR 3D PRINTED PROTOTYPE
- UNLESS OTHERWISE SPECIFIED:
Bibliography


George Hunyadi, David Klumpar, S. J. B. L. and Obland, M. (nd). A commercial off the shelf (cots) packet communications subsystem for the montana earth-orbiting pico-explorer (merope) cubesat.


Academic Vita

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Education

*The Pennsylvania State University, University Park, PA*
- Bachelors of Science in Aerospace Engineering, December 2011
- Honors in Aerospace Engineering
- Certificate in Space Systems Engineering
- Certificate in Engineering Design
- Schreyer Honors College
- Honors Thesis: The Design of Low Profile Deployable Systems for University CubeSats
- Honors Advisor: George A. Lesieutre
- Thesis Advisor: Sven G. Bilén

Projects and Positions

*Student Space Programs Laboratory*
- Mechanical Subsystem Functional Group Lead
- High Energy Monitoring Instrument
- OSIRIS CubeSat

Internships

*NASA Ames Research Center* (Summer 2010)
Moffett Field, CA
- CUIP Wireless Sensor System Intern

*STAR-H Corporation* (Summer 2009)
State College, PA
- Engineering Intern and Machinist

Awards and Scholarships

*Revolutionary Aerospace Systems Concepts Academic Linkage (RASC-AL)*
- Forum Competitor, 2011

*ET Foundation’s International Aluminum Extrusion Design Competition*
- Third Place Winner, 2008
- Class of 1922 Memorial Scholarship
- Irv and Barbara Susson Trustee Scholarship in Engineering
- Juanita M. and Tony Decillis Scholarship
- Aero Pioneers Class of 1944 Scholarship
- Schreyer Honors College Endowment for Academic Excellence Scholarship
- External Advisory Board Engineering Scholarship
- Schreyer Honors College External Advisory Board Scholarship

Professional Memberships and Publications

- National member of American Institute of Aeronautics and Astronautics (AIAA)

*Testing of a Wireless Sensor System for Instrumented Thermal Protection Systems*
AIAA Hypersonics Conference Paper, Coauthor