University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018 Fall 2016

# Project Definition Document (PDD)
# **O**ptical **S**ensor **P**ackage for **R**elative **E**xploration (OSPRE)

## APPROVALS

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## RELATED DOCUMENTS

| Name | Revision |
|---|---|
| Customer Requirements Document: “LM Sponsored CU ASEN Senior Project: Customer Requirements Document (2016-2017 academic year)” | 1 (02AUG2016) |
| ASEN4018 Course Assignment Document: “Project Definition Document” | 18AUG2016 |

# 1.0 Problem Statement

While small satellites such as CubeSats have gained popularity as lower-cost and lower-risk platforms for science payloads and technology testing, their limited mass, volume, and power often preclude the installation of traditional guidance and navigation systems. This is particularly problematic for deep space missions, during which GPS is unavailable. In order to be practical for such satellites, alternate sensors and computational methods must be employed to reduce the scale and cost of state vector determination. One such method is that of “angles-only” relative-navigation resolved from image data of nearby celestial objects acquired by one or more compact imaging sensors.

This project will develop and test a prototype navigational package, named Optical Sensor Package for Relative Exploration (OSPRE), to include the requisite hardware and software, which implements the technique of “angles-only” navigation. The OSPRE system will be designed for integration aboard a Lockheed Martin (LM) CubeSat vehicle. The primary mission of this satellite is to serve as a remote sensing test platform while executing a lunar flyby. The navigation system developed herein will provide the vehicle Guidance, Navigation, and Control (GNC) computer with regular updates to its state vector, including inertial position, velocity, position error, and velocity error for at least the duration of the primary mission including lunar transit and flyby.

The overall project and mission Concept-of-Operations (ConOps) is illustrated in Figure 1.1 below. The OSPRE navigation package will utilize a Commercial-Off-the-Shelf (COTS) microcontroller to command sensor acquisition and process imagery of the Earth and Moon, measuring both their size and location within the field of view. Provided a known vehicle orientation in terms of quaternions from the vehicle GNC computer, the sensor package will then determine the angles to each target, and compute the spacecraft position in the Earth-Centered-Inertial (ECI) frame. Consecutive measurements will be utilized to compute velocities in the ECI frame, and the state vector and state vector error will be passed to the vehicle GNC computer. Given the uncertainty that accurate initial conditions will be available upon vehicle deployment, the OSPRE system will not be designed with an over-reliance on these conditions for orbital propagation, but will instead rely primarily on its own relative solution and processing. When available, the imaging of other celestial objects such as sun angle and their respective angular positions may be utilized for error-checking and validation.

A successful OSPRE prototype will be shown to meet, at a minimum, all Level 1 objectives listed in Section 3, including the satisfaction of weight, volume, and power cost as well as data acquisition, processing, and state vector determination able to be passed on to the vehicle GNC computer in the required protocol and format. All prototype hardware, software, and associated test equipment will be delivered to the customer upon completion of this project in late Spring 2017.

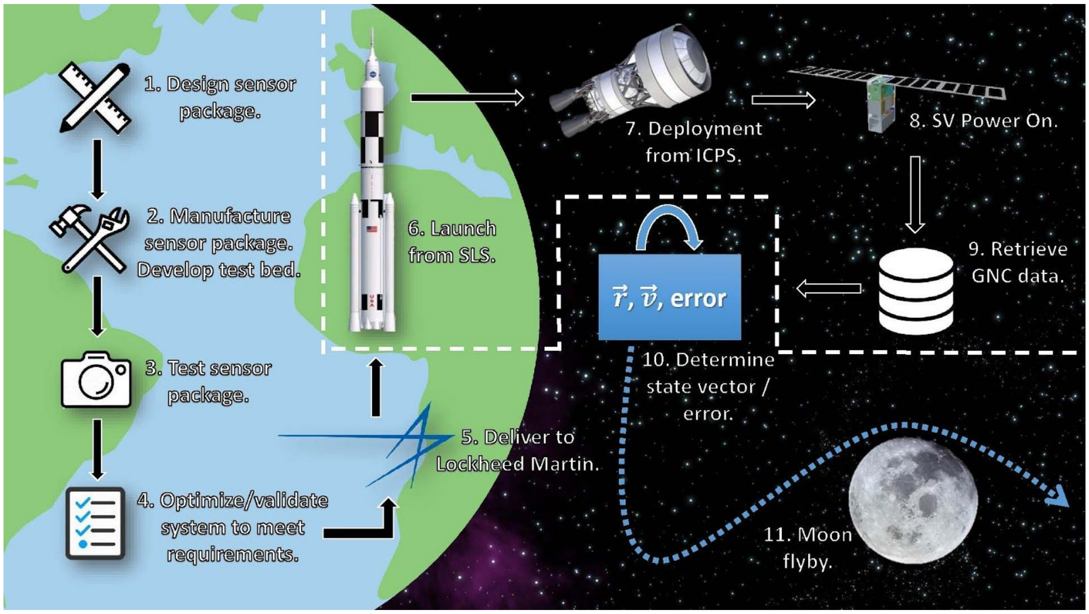

**Figure 1.1**: *OSPRE Mission ConOps*

## 2.0 Previous Work

The technique of angles-only navigation has been implemented in previous space missions including the Apollo missions, deep space probes, and autonomous docking with the International Space Station [1]. These early implementations were used primarily for rendezvous operations but the advent of high sensitivity imaging systems and computer algorithms eventually led to angles-only navigation being used as the primary navigation system for deep space missions. Numerous journal articles have been written on the algorithms, software, error, and problems associated with this method for space navigation, with a few referenced in this section. This library of information will be leveraged heavily to ensure the project builds upon past work and avoids problems encountered in previous attempts.

Additionally, several mathematical algorithms have been developed to solve the problem of angles-only navigation. The algorithms fall into two general categories: closed form linear solutions and nonlinear solutions. For example, Kaplan [2] created a closed form 3-D solution, which does not require knowledge of past positions, velocity vectors, or an attitude solution. Kaplan also provides methods of forward propagating random and systematic error in his solution. Tuckness, Young [3] and Bamford [4] created an angles-only navigation algorithm specifically for lunar transfer orbits implementing a nonlinear Extended Kalman Filter. A Kalman filter includes the forward propagation of uncertainties in each variable forward in time.

Prior space missions also offer a wealth of data regarding problems that were encountered, corner cases considered, and the limitations of this guidance method. A journal article written by Bhaskaran, Riedel, and Wang [5] details a post-flight guidance system analysis from the Deep Space I spacecraft. Issues addressed include image exposure, processing, blur correction, as well as the introduction of stray light from the sun. This analysis offers insight into the importance of camera selection, image processing, and robust pre-flight mission testing. Further research and trade studies will be necessary to determine the suitability of computational solutions for the OSPRE project.

## 3.0 Specific Objectives

Three levels of success have been defined in order to characterize the meaning of success for the OSPRE project. Level 1 is defined as the absolute minimum that shall be accomplished in order meet the project's base requirements. Level 2 is defined as an intermediate set of accomplishments that are critical to meeting the customer's given requirements. Level 3 is defined as the specific requirements, provided by the customer, that the team plans to accomplish to demonstrate the project's requested capabilities and ensure mission success. The system will be designed to the highest level of success (Level 3). The specific requirements for each level are listed in Table 3.1 below.

When developing the levels of success, the team set Level 3 requirements such that they align with the entire finished product outlined by the customer. Each level preceding was seen as a stepping stone to achieving the ultimate goals in each respective category. This was done to ensure the team had safety nets in place if a required goal was to become unachievable in the provided time frame. Level 1 goals were set because they were perceived to be comfortably attainable by the team. Each Level 1 requirement was set such that it would need to be completed before the next level can be attempted. The second level of success then signifies aspects of the project that the team recognized as the first challenges presented in each associated section. These include estimating error within our developed algorithm, maintaining the correct power draw, staying within given volume, and developing a testbed. The error estimation provides a challenge as there will be many hardware and software factors that propagate the error throughout the system which will be difficult to identify, while the power limits were deemed challenging as it is quite small and the team is still unsure on the total number of electrical components that will be used in the sensor system. Also, the volume constraint remains a large concern as our initial research informed us that the depth of 1 cm will limit the optical sensor choices that could have provided us with the desired resolution. The testbed is foreseen as the first testing challenge as it will be difficult to simulate the product's environment such that an accurate error can be measured. Once all Level 2 requirements have been met then the final system level requirements can be undertaken.

The Level 3 choices represent the final most difficult hurdles that must be completed to meet the requirements laid forth by Lockheed Martin. The data processing ultimate challenge will be maintaining the state vector within the given error due to the lack of top grade sensors available within our budget while also needing to minimize the algorithm's inherent error ranges. The final step for the electrical portion of the project will be to incorporate telemetry checks for vital components of the sensor system such that an imminent system failure can be recognized. This level of success would instill a sense of robustness in the electrical subsystem and would require additional time and development not pertinent to the operation as a whole. The final level of success for testing our system is critical to the success of our project but will be especially difficult to develop since the team will need to simulate the foreseen space environment for both the software and hardware simultaneously.

| | **Level 1** | **Level 2** | **Level 3** |
|---|---|---|---|
| **Data Processing** | OSPRE shall output a state vector for full Moon and Earth disks and shall gather data for no longer than an hour at a time. | OSPRE shall estimate the error of the state vector. | OSPRE shall provide the state vector error within an accuracy of 1000km and 250m/s and shall function for all Moon and Earth phases. |
| **Electrical** | OSPRE shall operate nominally provided 3.3V, 5V, or 12V electrical power, and interface with the ZedBoard and image sensor(s) using SPI, I$^2$C, or Cameralink. | OSPRE shall have a peak current of no more than 500mA and maximum power draw of no greater than 3W. | The system shall provide voltage sense and current sense telemetry. |
| **Structural** | OSPRE's mass shall not exceed 0.8kg. | OSPRE's dimensions shall not exceed 5cm x 5cm x 1cm. | - |
| **Testing** | OSPRE's testing shall include testing the accuracy of the algorithm.<br>OSPRE shall create a software test capable of quantifying the navigation software's error. | OSPRE's testing shall include a physical simulation.<br>OSPRE shall create an Earth-Moon testbed that quantifies the error of the navigation hardware. | OSPRE's testing shall incorporate hardware and software testing simultaneously.<br>The system shall compute the state vector autonomously in a test environment. |

**Table 3.1**: *OSPRE Project Success Criteria*

# 4.0 Functional Requirements

Figure 4.1 details the Concept of Operations (CONOPS) for OSPRE testing. OSPRE powers on and receives data (sun angle, attitude quaternion, time, and ephemeris) from a computer, which simulates the spacecraft GNC computer. OSPRE takes an image of its target and processes the image to determine its position. OSPRE is then moved to a different location to simulate the spacecraft moving and takes a second image. This image is processed to determine position and then compared to the first image to determine velocity. This process is then repeated and the state vector data is saved and uploaded to the computer.

The major functional elements of the OSPRE system and their interactions are illustrated within the context of the intended test setup in Figure 4.2. Several critical elements of the spacecraft and their interaction with the OSPRE system are included for reference. However, these will be replaced by bench-top power supplies, the test console computer, and other test equipment as necessary for the purposes of this project.

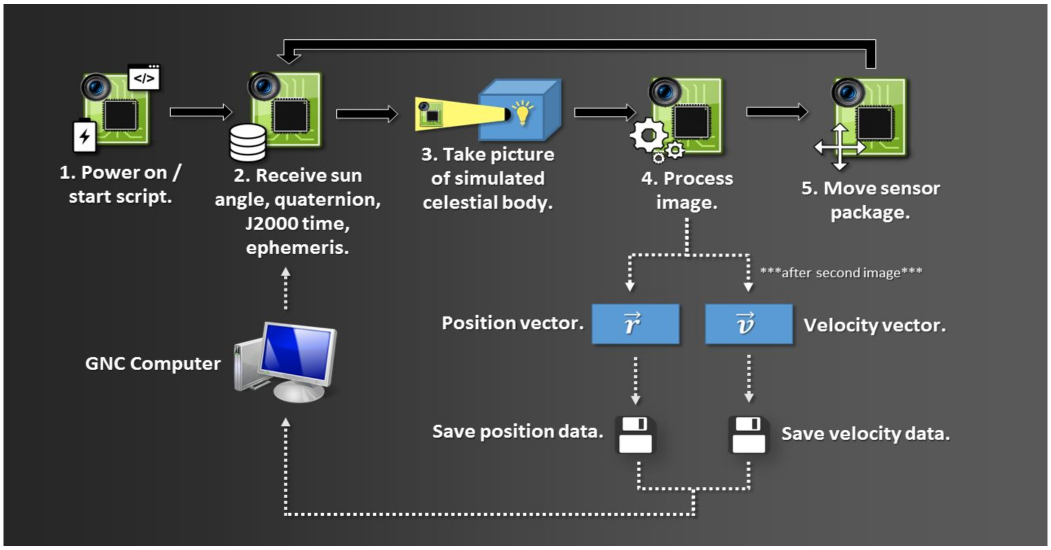

**Figure 4.1**: *Concept of Operations for OSPRE Test*

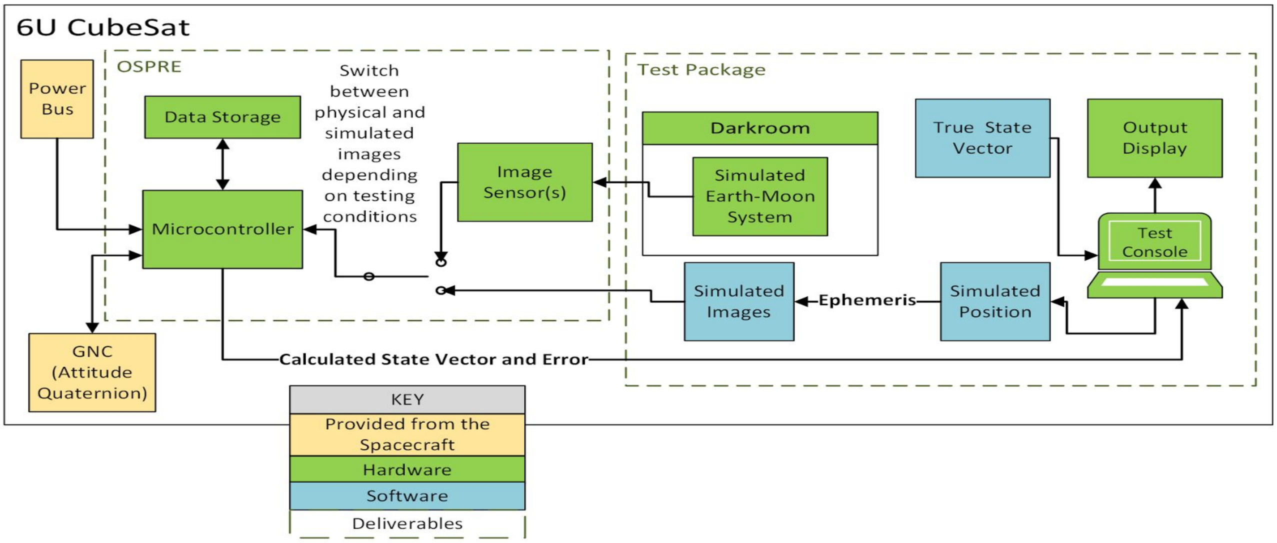

**Figure 4.2**: *OSPRE System Functional Block Diagram*

The OSPRE deliverables can be described in two main paths: the test package and the sensor package. Contained within the sensor package is the image sensor, temporary data storage, and a microcontroller that process images. During testing, images will either be simulated through calculating scale images in software, or by creating a darkroom environment with projected images. These images are then passed to the ZedBoard test console where they are post-processed and handled by the algorithm to return the state vector and state error. The simulated spacecraft will also provide power and the GNC attitude quaternion to the sensor package.

# 5.0 Critical Project Elements

## 5.1 Data Acquisition

In the timeline of its operations, both in testing and in flight, the first thing that OSPRE must accomplish is proper data acquisition. This primarily entails collecting images of the Earth and Moon, or analogs thereof used in testing, with adequate spatial resolution and edge contrast in order to measure the diameter of, and locate the geometric center of these objects. If the spatial resolution or edge contrast is not high enough, the system will be unable to determine its state vector to within the required error. The anticipated challenges involved in this process in order to meet that task include hardware selection that meets volume requirements, configuring and controlling the chosen image sensor, and accounting for thermal and optical effects of the space environment.

## 5.2 Interfacing

The various hardware, software, and personnel elements of OSPRE will require large amounts of interfacing in order to be successful. Communication and collaboration between all involved parties will necessitate patience and flexibility. Finding compatible hardware and ensuring that they properly communicate is expected to pose a challenge. Electrical interfacing and communication between the microprocessor and sensor package, as well as between the sensor package and the vehicle data bus, will necessitate embedded systems knowledge and hardware-software interfacing with which few of the OSPRE team members have experience.

## 5.3 Software Testing and Validation

An angles-only relative navigation algorithm for use on a CubeSat on a lunar flyby trajectory will be designed and implemented. The difficulties associated with this process are expected to include accurate object recognition, developing and understanding the mathematics behind the selected algorithm, and the technical complexities of developing software which can perform the necessary image processing, and can handle edge cases while verifying its own result. These difficulties are both technical and logistic in nature. The technical challenges include requiring knowledge of algorithm construction, software efficiency and optimization methods, and advanced spatial mathematics techniques. In particular, creating an algorithm that can identify and characterize the Earth and Moon in all Earth/Moon phases and when only a portion of the celestial body is in the frame is expected to pose a significant challenge. The associated logistical challenges concern the large amount of time it will take the OSPRE team to properly implement and test the software/algorithm functionality.

### 5.4 Testing and Validation

A simulation of the the trans-lunar trajectory and environment in which OSPRE will function is necessary in order to validate the navigational capabilities of the system overall. However, this environment is complex and therefore difficult to simulate, particularly with respect to optical phenomena and noise that image sensor may encounter in flight. Physically modeling the Earth and the Moon requires precise scaling, while virtually modeling the cislunar environment requires generating a large amount of accurately simulated images, and both physical and virtual modeling must accurately represent the predicted spacecraft dynamics. The accuracy of this testing, whether virtual or physical in nature, is critical to determining the intended vehicle position and velocity, and thus critical to verifying that the solution computed by the OSPRE navigational package is within the required error band.

## 6.0 Team Skills and Interests

The following table outlines team member skills. All team members are listed at least once.

| **Critical Project Elements** | **Critical Skills** | **Team Member(s) and Associated Skills and Interests** |
|---|---|---|
| Data Acquisition | Optics Knowledge<br>Image Processing | D. Walden - professional photography experience<br>D. Richards - performed trade studies on various optical setups<br>R. Cutter - image processing, closed-loop frame manipulation<br>M. Ricciardi - studied/worked in imaging at RIT |
| Interfacing | Communication Protocol Knowledge and Interfacing Microprocessor with Optical Sensor | S. Zegelstein - Networks: TCP/IP, Datagram and Multicast<br>Z. Folger - currently enrolled in microavionics course<br>R. Cutter - SPI, UART/USART, I2C protocols, Altium PCB design<br>A. Torres - UART/USART, I2C, Altium design |
| Software Functionality | Programming Knowledge and Algorithm Development | S. Zegelstein - C, C++, JAVA, Matlab<br>P. Arthur - concepts of rel nav algorithms for SkyFire<br>A. Torres - C, C++, Java, Python, Matlab, control modelling<br>C. Maywood - C, C++, Java, Python, Matlab |
| Testing and Validation | Testing Knowledge, Physical Test Concept and Construction, and GNC Simulations | M. Ricciardi - professional experience with engineering test<br>D. Walden - test design & assembly experience<br>Z. Folger - virtual software testing (STK)<br>P. Arthur - GNC MATLAB simulations for SkyFire<br>A. Torres - test, CAD, and Simulink experience |

## 7.0 Resources

| **Critical Project Elements** | **Resource / Source** |
|---|---|
| Data acquisition | Dr. Jeff Thayer (Remote Sensing knowledge), Dr. Xinlin Li (Remote Sensing knowledge), Lee Sutherland (optics and imaging), Milos Popovic (optics) |
| Interfacing | Trudy Schwartz (Microprocessor knowledge), ITLL instruments (oscilloscopes, multimeters, power supplies), Altium PCB Design Tool |
| Software functionality | OpenCV, Dr. John Evans (software expertise), NASA (open source code), Gemmill Library (technical papers) |
| Environment simulation | Dr. Jay McMahon (GNC knowledge), Dr. Steve Nerem (GNC knowledge), Matt Rhode (Aerospace Machine Shop and Test setup), Dale Lawrence (ADCS), Bobby Hodgkinson (test construction), STK (System Tool Kit), ECEE 2B49A (Darkroom) |

# 8.0 References

[1] Woffinden, David C. and Geller, David K. “Relative Angles-Only Navigation and Pose Estimation for Autonomous Orbital Rendezvous” *Journal of Guidance, Control, and Dynamics* Vol. 30.5 (2007): Web. Aug. 2016

[2] Kaplan, George H. "Angles-Only Navigation: Position and Velocity Solution from Absolute Triangulation." *Navigation* 58.3 (2011): 187-201. Jan. 2011. Web. 30 Aug. 2016.

[3] Tuckness, Dan G., and Shih-Yih Young. "Autonomous Navigation for Lunar Transfer." *Journal of Spacecraft and Rockets* 32.2 (1995): n. pag. Web. 30 Aug. 2016.

[4] Hur-Diaz, Sun., Bamford, Bill., Gaylor, Dave. “Autonomous Lunar Orbit Navigation Using Optical Sensors” : Web. Sep. 2016

[5] Bhaskaran, S., Riedel, J. E., Synnott, S. P., Wang, T. C. “Deep Space I Autonomous Navigation System: A Post-Flight Analysis” *American Institute of Aeronautics and Astronautics* (2000): Web. Aug. 2016