University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document (PDD)

GHOST - Ground Hardware for Optical Space Tracking

Approvals

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1 Problem Statement

As the space industry continues to grow, Space Traffic Management (STM) and Space Situational Awareness (SSA), for the purpose of conjunction avoidance, are becoming areas of increased interest. The US is dependent on our assets in space for navigation, weather forecasting, national security, and countless other daily needs. If a collision in space were to happen, the result would be catastrophic, propagating throughout the many operational orbits in space. In order to mitigate the risk of a space collision as space becomes increasingly essential to daily life, The Aerospace Corporation is currently exploring a variety of SSA sensor options. The overarching goal is to identify technologies and systems that can meet a growing demand for more frequent and more accurate space object orbit tracking. The SSA market currently relies on expensive ground systems that exist in low quantities throughout the world. Thus, there is an empty niche for low-cost, high production-volume sensors. SSA is ultimately performed to generate actionable intelligence; it assists in answering questions for satellite operators such as:

- What is my satellite's current orbit?
- Did my satellite's orbit change as expected given the recently commanded maneuver?
- What are the potential upcoming collision risks based on my current orbit?

The primary science goal of the Ground Hardware for Optical Space Tracking (GHOST) project is to obtain an updated orbital state of cataloged resident space objects for the purpose of increased forecasting accuracy for space traffic management. Using the sensor's latitude and longitude in addition to observed right ascension and declination of the space object at a series of points in time, the system shall perform a specific orbit determination (OD) and return the orbit state to a database. By increasing the frequency and number of observations, the covariance or positional uncertainty for any given object will be reduced. The increase in observational frequency will ultimately be achieved using a large network of small, low-cost optical tracking systems. While a low-cost sensor may not be able to achieve the same range of observations as a high-cost sensor, the ability to cover a high percentage of space objects would allow for both increased frequency of observations and increased availability of high-cost sensors for challenging tasks. The GHOST SSA sensor will track resident space objects in LEO, MEO, and GEO orbits when visible with a visual magnitude of less than 10 at a cost of no more than $5000.

The GHOST system design will include two major components: an optical system capable of capturing the visual signatures of orbiting satellites, and a software package that will perform scheduling and orbit determination. This problem presents an end-to-end challenge, requiring knowledge and expertise across a variety of fields and disciplines including controls, astrodynamics, optics, and manufacturing.

2 Previous Work

Current SSA systems use multiple types of sensors, but primarily rely on high-fidelity optical imaging for high altitude space objects. The optical imaging sensors are both large and expensive, weighing hundreds of pounds and occupying small buildings while costing upwards of $100,000 for basic commercial and university setups. While these systems are fully capable of surveying and gathering data on the SSA environment, the current size and cost of such systems limit the extent to which they can be distributed around the world.

Space Situational Awareness has become an important issue for world leaders to address in recent years, with the Department of Defense committing around $6 Billion on efforts to monitor space in real-time[3]. This undertaking represents one of the most comprehensive endeavors in SSA to date. This change in priority emerges as the space environment becomes more "contested, congested, and competitive", with the Combined Space Operations Center issuing 671,000 notifications of potential space environment collisions in 2014 alone. As of late 2015, the government owned 375 sensor systems, all maintained by the military. The Aerospace Corporation would like to examine the potential of using low cost, high production-volume sensors for the purpose of improving the accuracy of conjunction forecasting.

Other parties tackling problems related to SSA include the European Space Agency (ESA), which publishes an annual "report on space junk" [4]. The ESA draws on data collected from multiple universities and institutions across Europe to synthesize into the report. Prior work available for reference includes orbit propagation, amateur astronomy imaging, SSA image processing and orbit determination. The focus of this group will be to use information gleaned from more expensive operational systems combined with a low cost approach to attempt to miniaturize and reduce cost of the minimum capable system.

Additionally, many commercial ventures are currently working on components of space traffic management. Companies such as ExAnalytics and Analytical Graphics, Inc. (ComSpOC) are both working to develop commercial sensor networks and operations centers capable of provide subscription based space monitoring to satellite operators. These commercial projects will provide useful context on the capabilities of prior systems at varying cost levels.

3 Specific Objectives

Listed below are pivotal objectives that must be accomplished for a successful project, followed by a tabulated version with levels of success. GHOST will target a Level 3 success for the end of the project in Spring 2019 - should a reduction in scope be required, Levels 1 and 2 will guide completion metrics.

1. **Scheduling Software** - Given a set of NORAD IDs, gather orbit parameters from Space-Track.org to propagate and predict when and where the satellite will appear in the local sky. Use this information to create a schedule for image capture.
   - Verification method: *Comparison*. The output of the scheduler software will be compared with an off-the-shelf modeling software such as Systems Tool Kit (STK).
2. **Tracking Hardware** - The hardware will have the ability to autonomously track satellites while supporting the imaging system.
   - Verification method: *Analysis*. The tracking hardware will be tested in a lab environment for the ability to meet tracking rate and precision constraints.
3. **Optical System** - Collect a chronological series of images of the space objects that are being tracked with specified visual magnitudes.
   - Verification method: *Demonstration* and *Evidence*. This will be a completed objective if the team can demonstrate the system's image capture ability as tested in an outdoor field test. Publicly available online sources will be used to select objects of known visual magnitude for field testing.
4. **Image Processing** - Raw captured images will be processed, resulting in a set of right ascension and declination points for use in orbit determination. (right ascension, declination, time)
   - Verification method: *Demonstration* and *Comparison*. The results of a field test will be compared to the simulated output in a modeling software such as Systems Tool Kit.
5. **Orbit Determination** - Use observations to generate orbital information through a standard Orbit Determination method.
   - Verification method: *Demonstration* and *Simulation*. For development testing a set of simulated observations consisting of RA/Dec/Time will be used for an orbit determination and compared to the expected result. For full system testing an end-to-end test will be conducted in Colorado.

Table 1: Specific Objectives with Levels of Success

	Level 1	**Level 2**	**Level 3**
Scheduling Software	- Propagate an orbit state - Provide a imaging task list based on basic horizon constraint	- Incorporates multiple satellites in given timeframe	- Apply prioritization to imaging target selection based on human input and last seen time
Tracking Hardware	- Track objects in GEO orbits with automated slew between objects	- Track objects in MEO orbits	- Track objects in LEO orbits
Optical System	- Capture images of a satellite visible to the naked eye (visual magnitude less than 6.0)	- Autonomously adjust exposure length	- Capture images of a satellite visible with a binocular (visual magnitude less than 10.0)
Image Processing	- Report boresight right ascension and declination for each capture with TBD angular accuracy	- Report object right ascension and declination with TBD angular accuracy	- Report angular rate of tracked object with TBD angular accuracy
Orbit Determination	- Report object right ascension and declination (No orbit determination)	- Performs an unfiltered orbit determination based on angular observations	- Completes a full orbit determination using advanced filtering (i.e. Kalman or Batch)

Note - All levels of success assume complete end-to-end automation of system.

4 Functional Requirements

4.1 Requirements

1. The system shall track resident space objects from the Space-track.org space object catalog in Earth orbits with visual magnitudes of less than 10.
2. The system shall autonomously track and image resident space objects in GEO, MEO and LEO orbits.
3. The system shall provide angular measurements of a space object with an accuracy of TBD.
4. The system shall provide an orbit state estimate of a space object based on angular measurements and sensor location.
5. The scheduling software shall be able to autonomously schedule tracking given a list of space objects.
6. The system shall use a commercial-off-the-shelf (COTS) telescope and imaging system.
7. The system shall have the ability to know and report its own position.
8. The GHOST module hardware shall cost less than or equal to $5000.

4.2 Functional Block Diagram

Below is the functional block diagram for the GHOST SSA Sensor system. The GHOST hardware is an individually functional hardware system that is commanded externally and can function in a networked capacity. The GHOST system consists of both hardware and software. The hardware includes a COTS image sensor and telescope, an actuator system to target azimuth/elevation, and an enclosure. The software includes orbit propagation, a scheduling agent, pointing software, and a collection of APIs for hardware operation. The environmental sensors allow the device to perform the imaging for a given task list in a completely automated fashion. GPS time is used to synchronize all components for the sake of accurate orbit determination.

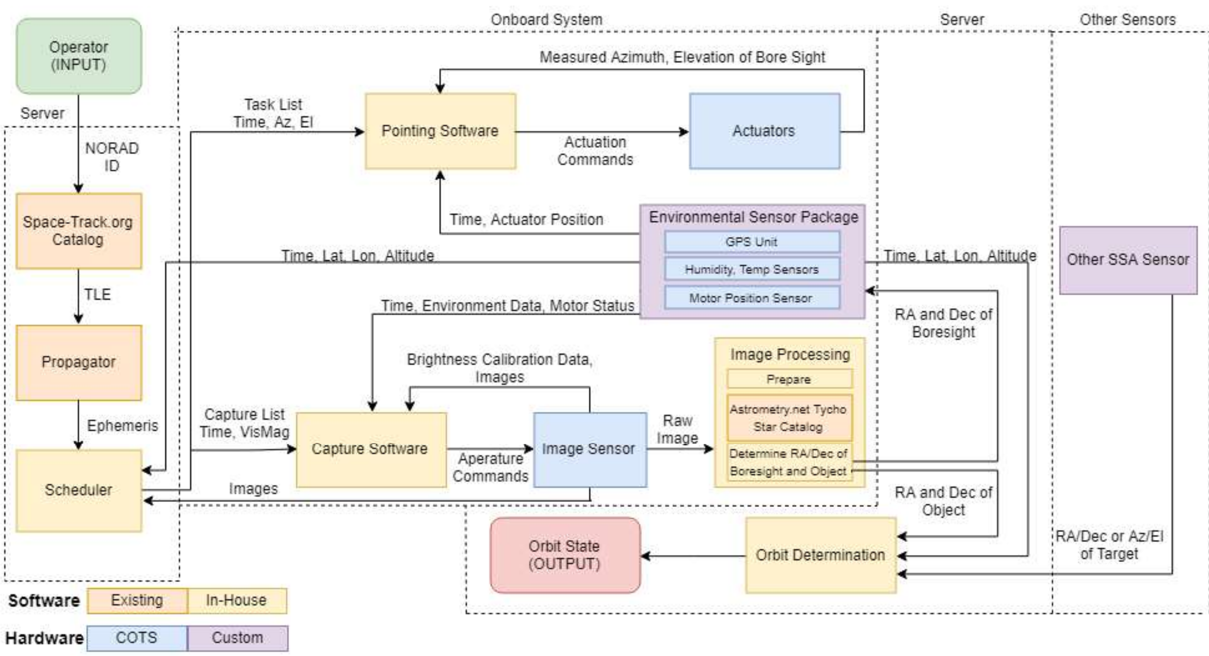

Figure 1: Functional Block Diagram for GHOST

4.3 Concept of Operations

Below is a project level and global level Concept of Operations (CONOPS). The project level CONOPS illustrates the desired functionality for completion of the project in April 2019. The operations will be tested locally in the Colorado region. The global level CONOPS illustrates the continuous operation of an SSA network using GHOST sensors and the use of the information provided by the GHOST sensors.

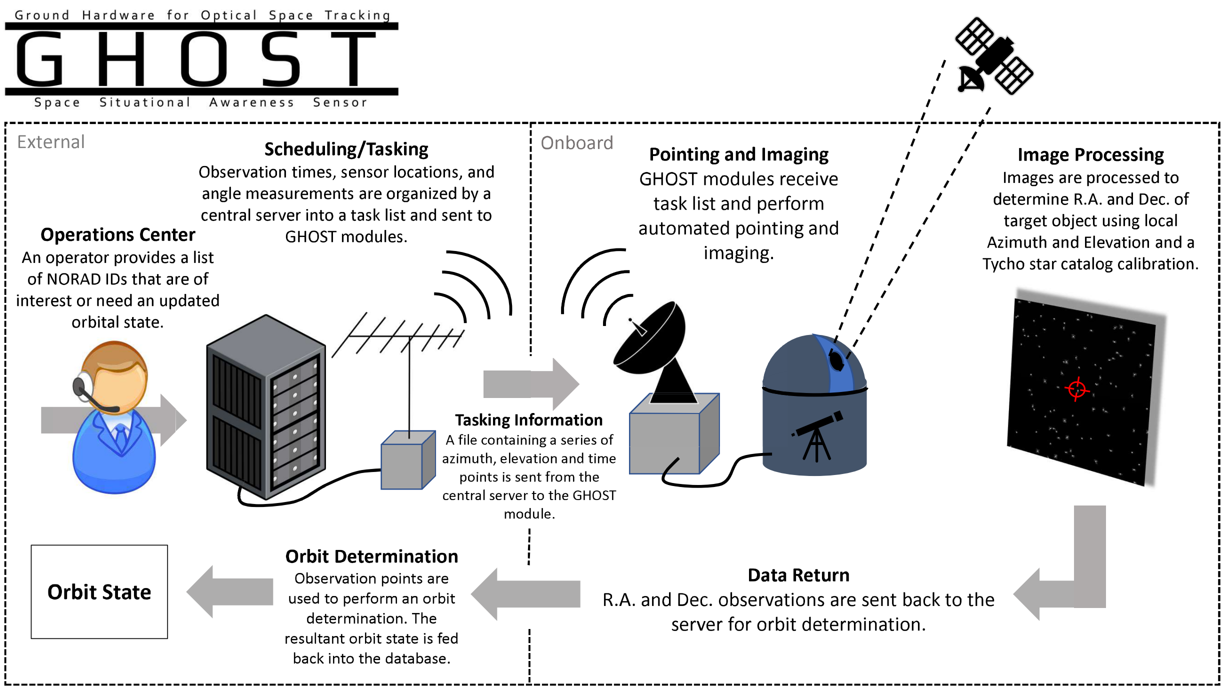

Figure 2: Concept of operations for GHOST.

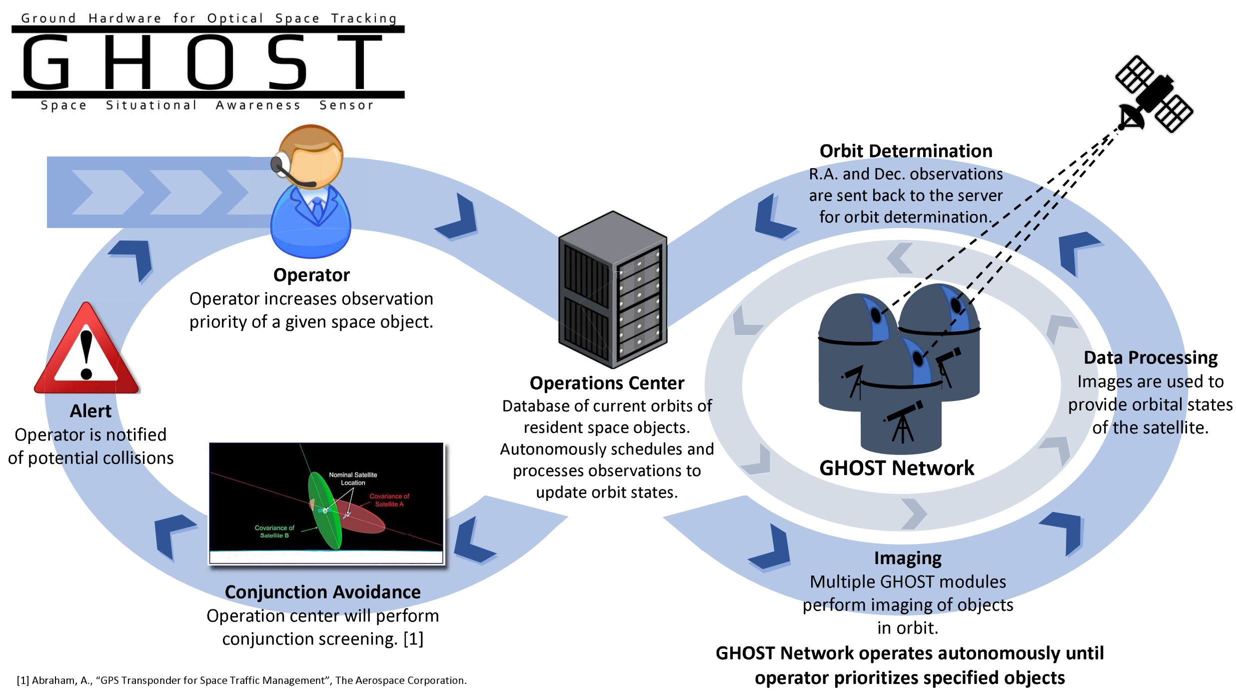

Figure 3: Global Concept of operations for GHOST Networking.

5 Critical Project Elements

5.1 Tracking Actuators

The tracking actuators must be able to accurately slew such that the desired object is in the field of view for image acquisition. The autonomy of control is a key requirement for the project capabilities - the sensor must be able to orient itself to accommodate a large turnover of objects to be tracked.

5.2 Integration Hardware

The integration hardware includes the mounts and parts that combine the optical hardware, actuators, receivers, and processors together into a self supported assembly. The integration hardware is critical to project success. Without the integration hardware, the system lacks stability and the ability to point and track with accuracy defined in the levels of success. This is also financially critical, as the cost of this structure cannot be considered negligible.

5.3 Optical Hardware

The optical system must be able to image satellites that are in a variety of Earth orbits. The optical hardware will produce an image from which azimuth and elevation can be determined. The optical hardware is also critical to the financial aspect of this group. The current optical hardware used in the field costs orders of magnitude more than the budget for this project. Finding adequate hardware that both meets the project requirements and fits within the budget is essential.

5.4 Scheduling Software

Given a TLE which allows for propagation of an objects orbit, there must exist a scheduling software to output azimuth, elevation and capture time commands that can be fed into the hardware control system. This software will have knowledge of the control system capabilities such that it can schedule image captures consecutively without timing conflicts. This software will also have knowledge of when an object will be in-view, knowledge of lighting, and knowledge of object priority.

5.5 Image Processing

To perform an orbit determination, images must be processed in such a way as to deliver right ascension, declination, and capture time to the orbit determination software. An additional conversion to azimuth and elevation may be included as a feature. If this is not achieved, no orbit state variables can be output and the project will be a failure.

5.6 Orbit Determination

Orbit Determination is critical element of the project as it is both challenging and essential to the success of the project. The orbit determination system will deliver an orbital state for each satellite tracked - these orbital elements will be the final output of the system.

6 Team Skills and Interests

Team Member	Skills and Interests	Critical Project Element
Connie	C, Data Analysis. Interest in image processing, orbit determination, orbit propagation, & autonomous control	5.1, 5.4, 5.5, 5.6
Connor	C, C++, Data Analysis, Astrodynamics & Satellite Navigation master's focus, image processing, orbit determination, & autonomous control	5.6, 5.1, 5.5
Duncan	Python, data analysis, neural networks & machine learning, CAD with manufacturing drawings, encrypted networking, testing & verification	5.2, 5.3, 5.5, 5.4
Ginger	Systems, object oriented programming, python, data analysis, orbit determination, controls	5.6, 5.1, 5.4
Jack	SSA Image Processing, Systems Engineering, Sensor Masking & Constraints Simulation, Orbit Determination	5.6, 5.5, 5.4
Jake	Machining & Manufacturing, Structural Design, Data Analysis, Systems Engineering, Testing Systems, Astrodynamics	5.6, 5.1, 5.2
Keith	Controls master's focus, Electronics, C, Data Analysis, Machine Learning	5.1, 5.4, 5.5, 5.6
Kira	Experience with Precise Orbit Determination, Astrodynamics, and GPS Analysis	5.6, 5.3, 5.5
Lucas	Computer Numerical Control, Electronics, Data Analysis and Testing, Fluids	5.1, 5.2
Rachel	Attitude determination, guidance & navigation, controls, optics, optical navigation, orbit determination, Kalman filtering/ bach filtering	5.1, 5.3, 5.5, 5.6
Seth	Structural Design, Manufacturing, Electronics, Testing, Financial	5.1, 5.2, 5.3, 5.5

7 Resources

7.1 Aerospace Labs

CU Boulder Aerospace Machine Shop and Electronics Lab will be used for the development and initial prototyping of the imaging system, environmental sensors, actuators and mounting structure.

7.2 ITLL and IdeaForge Labs

CU Boulder ITLL and IdeaForge lab spaces will be used for quick turn around development when the Aerospace labs are not available or in high demand.

7.3 The Aerospace Corporation Data

The Aerospace Corporation will provide a selection of relevant imagery taken on current R&D SSA sensors and observations for objects being tracked by the GHOST sensor. The imagery will be used to begin software development before hardware is available for testing. The observations for objects being tracked by GHOST will be used to test the multiple sensor orbit determination capability. This resource is vital for system testing.

7.4 Local Outdoors

Once the hardware development effort has begun, local outdoor spaces will be used for tests of the GHOST system. A variety of environments will be used to test masking capabilities, light pollution effects, and the ability of the imaging system to automatically adjust to the local environment. This will be the primary method of end-to-end testing used to validate the GHOST system.

7.5 Space-Track.org

Space-Track.org maintains a catalog of resident space objects. The catalog is publicly accessible and can be searched using NORAD IDs. The system will be able to use the orbit states provided by Space-Track.org for orbit propagation and scheduling.

7.6 Dr. Marcus Holzinger

Dr. Holzinger is a CU Boulder professor with research interests in Space Situation Awareness. Dr. Holzinger has experience with many of the processes and components required for the success of this project and will thus be an important resource throughout this project.

7.7 Harvey Mamich, Orion GNC Engineer

Harvey Mamich is a Lockheed Martin Engineer working on the Orion GNC system. Mr. Mamich over 28 years of experience in industry and experience with low cost Star Trackers and has valuable optics experience to convey to the group.

References

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