Recovering Time and State for Small Satellites in Deep Space

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ABSTRACT

Autonomous navigation in the satellite world is at best, a semi-autonomous solution. All systems currently require an outside presence or prior state to get a navigation. As the small satellite revolution brings about numerous more spacecraft, the need for truly autonomous navigation becomes a greater necessity for deep space travel as communication resources become limited. When spacecraft are in deep space, communication times between a satellite and the Earth can be prohibitive and ride-sharing opportunities as well as on-board faults can leave the spacecraft without time information. The proposed approach uses optical observations of available planets and corresponding celestial satellites (for interplanetary operations) to initially recover the approximate time and state. These observations are then followed by precise, filter-based determination of time, position and velocity from the chosen optical beacons available in interplanetary spaceflight.

The innovation of this approach is to use the periodicity of celestial bodies and artificial satellites to initially determine time. This capability is analogous to that of advanced star trackers that can initialize themselves by identifying any star field in the celestial sphere. Being able to quickly and autonomously recover time and position from an environment with no Earth contact will advance mission safety and automation from current methods which require an Earth contact. The impact of this concept crosses both human (full loss of communication scenario) and robotic (autonomous recovery from onboard fault) exploration applications, where some form of spacecraft-to-ground communication is required to establish approximates for time and position. In both cases, the current state-of-the-art navigation systems require some knowledge of time and some approximate position to initialize the estimation process before the mission objectives can be obtained. This presentation will examine the best-known solution for time in different scenarios related to the future of small satellite missions. While the solution is applicable to a wide range of missions, small satellites used for solar system exploration will be the focus as small satellite solutions can then be scaled to larger spacecraft.

INTRODUCTION

The advancement of small satellites and new capability of deep space travel presents unique problems not present on larger class satellites. For cubesats on the EM-1 launch of the NASA SLS rocket, time and state (position and velocity), are not given to the cubesats upon initial deployment from the rocket. This leaves the satellites in a precarious position with no time and state knowledge to communicate back with the Earth.This could severely hinder initial communication with the cubesats. The fundamental premise of this research was born out of this concern, but has lead to a plethora of situations where a satellite could lose time and state and become “lost-in-space” including:

1. Memory corruption: Single event upsets can cause a corruption of data stored in flight software. Such corruption can result in a spacecraft losing knowledge of time, position, and velocity (PVT).

2. Processor reboot: Flight computers can reboot unexpectedly for several reasons including single event

upsets, watchdog timer reset or a lack of power due to a poor attitude configuration or short.

3. Initialization State: Many rideshare opportunities do not allow for initial state to be given to the smallsat, such as the EM-1 launch described above. These satellites will be deployed out after the main Orion payload with no initial PVT and must recover PVT to begin communication.

The objective of this research is to find and mature a solution of the lost-in-space orbit determination problem for low size, weight, and power (SWaP) resource limited satellites. This will be done by investigating feasibility and developing the algorithms plus the concept of operations required to demonstrate autonomous cold-start determination of time and state (position and velocity) for interplanetary missions, dubbed the "Lost-In-Space" orbit determination problem. The research with utilize an autonomous optical navigation system designed to utilize readily available hardware for small satellites.

Losing satellites in deep space is not improbable,[1] finding and recovering them is rarer, with just a few examples[2] in the past few years of satellites that had been lost for decades. In the case of the STEREO-B satellite, it took 25 attempts of a Deep Space Network frequency segmented sweep to re-establish communication. In total these sweeps took over 10 hours for each attempt to reestablish communication with STEREO-B. With mission assurance and risk always at the forefront of mission designers, having a way to reliably estimate position, velocity and time without the aid of ground-based resources could significantly reduce these losses of satellites and shorten recovery attempts. Furthermore, the growth of small satellites and the driving scientific interest to use these satellites for solar system exploration necessitates the development of alternatives to using the Deep Space Network (DSN) to determine the spacecraft position. There are simply not enough DSN resources available to support the future growth.

AUTONOMOUS NAVIGATION

Autonomous navigation is described by the following features[3]

- Self-Contained
- Operates in real time
- Nonradiating (Does not produce signals that aid in navigation, i.e. range/range rate between satellites)
- Independent of outside operations

When applied to a spacecraft, a system is considered autonomous when navigation is performed on onboard the spacecraft in real time and without ground support.[4]

Autonomous navigation for deep space satellites is a technique that has been used on satellite missions in the past such as Deep Space 1, Deep Impact and STARDUST.[5] Additionally satellites such as Voyager 1 and 2 have demonstrated optical techniques for navigation.[6] Autonomous navigation currently has no way to autonomously determine time/position/velocity without prior information from ground-based systems. Additionally, these current systems have only been used sparingly and during approach and encounter of the final target where the time delay between Earth and satellite is unacceptable to meet the mission needs.

The only current approach for the “lost-in-space” problem solves position but not time.[7] This paper goes through a solution that uses several known beacons to determine position and attitude. Once a set of solutions is obtained, a closed-form solution using line of sight distances derives the solutions explicitly instead of providing the solution in terms of polynomial roots. Without knowledge of time the position solution is only a relative solution and does not provide absolute position. This is important because in order to have a full solution to the lost-in-space problem, there must be an absolute time to relate the position and velocity back to, otherwise there is an infinite solution space that exists into the future for a relative solution.

APPROACH

Based on the limitations for small satellite hardware, optical measurements from star trackers and measurements to the Sun are selected as the information used to solve for the “lost-in-Space” problem. The approach selected herein is to solve the “lost-in-space” PVT problem using the Jovian system. Because Jupiter is a bright object, it can be easily found with low size, weight, and power (SWaP) current star tracker technology. Solving for just position and velocity only yields a relative solution. For motivations that rely on communication, it is imperative that an absolute solution be made available, as just a solution relative to Jupiter is not sufficient to determine how to point the spacecraft if one wants to communicate with the Earth.

The proposed solution assumes a satellite that has come up from a cold state without any knowledge of PVT. This approach would also require that an ephemeris catalog of stars and planets be loaded on the spacecraft prior to launch and accessible. It is possible to write the state vector to non-volatile memory, but if the spacecraft is down for weeks or months it would not have accurate time. However, with a prior state vector available, the navigation system would be able to bound the problem to the last possible known time, thus decreasing the extent of the feasible solution space that must be explored to determine the current PVT state.

Lost-in-Space Solution Approach

The approach that will be taken to solve the lost-in-space problem is as follows

1. Determine attitude (star tracker)

2. Locate sun-line direction (coarse sun sensor)

3. Estimate min/max distance from Sun (radiance)

4. Estimate satellite distance from Jupiter

5. Compute search/scan angle to find Jupiter

6. Scan with star tracker, then image process

7. Detect and estimate the location of Jupiter

8. Image the Jovian system

9. Detect and estimate the location of additional objects if necessary, i.e. Mars, Saturn, natural satellites.

10. Estimate PVT

It should be noted that this above approach is only to reduce the time to recovery. An entire sky scan could be done to identify objects but the time to correctly identify each object would be much longer and increase time to recovery.

FEASIBILITY

For mission planning purposes, it is important to know the visible availability of a proposed object, in this case Jupiter. Using a simple geometric representation of a satellite, Jupiter, and the Sun, the percentage of Jupiter's orbit that would not be visible because of the keep-out area of a star tracker was determined. Using the models in figure 1 and figure 2, the percentage of Jupiter's orbit that the satellite would be able to see are shown in Table 1. The baseline star tracker used for this analysis was the Sinclair star tracker which has a keep out area of 22° or 34° depending on the model selected,[8] this is denoted as θ in the figures.

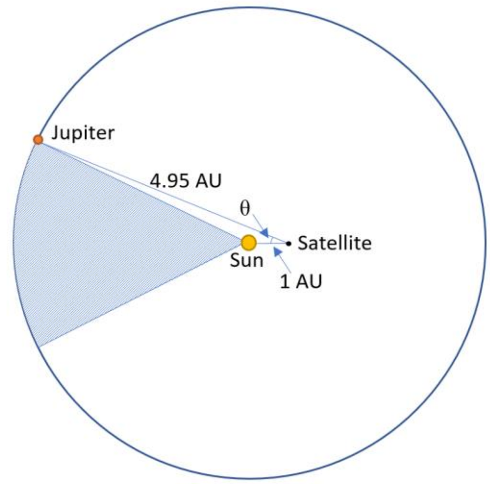

Figure 1: Jupiter Visibility from 1AU

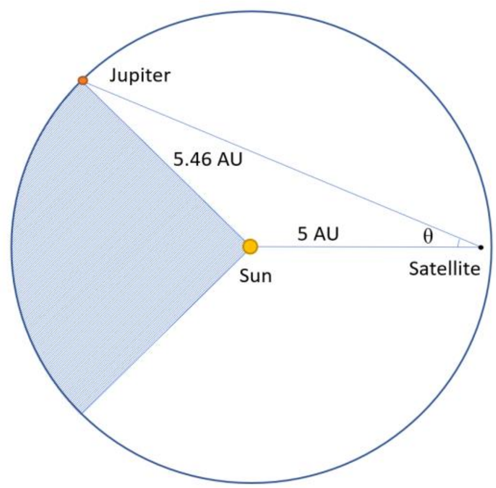

Figure 2: Jupiter Visibility from 5AU

Table 1 shows the percentage of availability that a satellite would be able to see Jupiter, with distances between 1 AU and 5 AU being a linear relationship to the percentages associated with each distance.

Table 1: Percentage of Jovian Visibility from Satellite Using a Sinclair Star Tracker

Satellite Distance	Star Tracker Keep Out	
	22°	34°
1 AU	14.6%	22.7%
5 AU	24.4%	37.8%

In order to start a solution for time, an initial position, to some uncertainty, of the satel-lite will have to be solved for. Without an initial position, when the satellite views Jupiter to start a time solution, there are an infinite number of sceneries that the satellite could view Jupiter and receive the same information. To gather enough information, scalar and vector from the Sun is needed along with attitude information from the star tracker. As shown in Figure 3, this will bound the problem to a finite solution space along a line. This approach to get an initial position is preferable to using Jupiter as Jupiter can easily be identified as it is the only planter system that the moons can be seen with a cubesat star tracker.

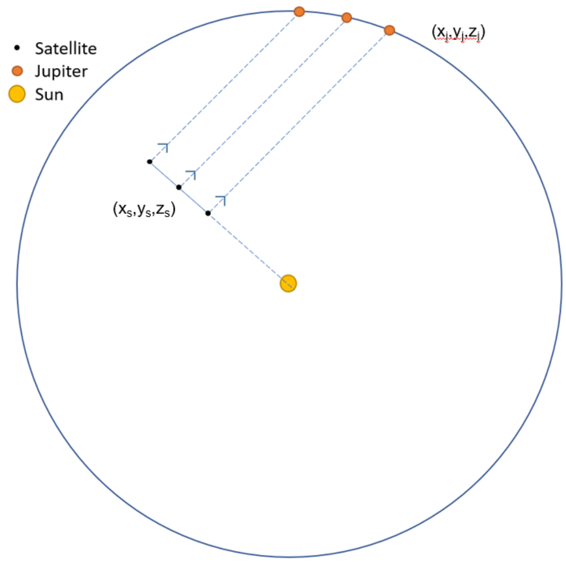

Figure 3. A representation of the approximate position solution area that the spacecraft would be able to solve for using an irradiance measurement from the Sun. (Not to Scale)

Once the initial position area is calculated, the following need to be done to get a stationary bound for a time solution.

1. Calculate the satellite position difference from ephemeris truth data of Jupiter for all positions of Jupiter. This will give a vector ephemeris set.

2. Compare to vector star tracker data received from Jupiter to the ephemeris data set.

3. Match the vector solution to the closest calculated ephemeris vector solution

4. Bound the solution space with an irradiance measurement from the Sun

5. Convert vector solution space to upper and lower time bounds based on ephemeris data.

In doing this, the bounds of time were calculated as follows in Table 2, given an irradiance error and distance from the Sun. It is important to note that each number is the bound in one direction, so to get a full bound the number will need to be doubled.

Table 1: Time bound given an irradiance error and distance from Sun.

	.1% Error	1% Error	5% Error	10% Error
1 AU	1.5 hours	16 hours	74 hours	6 days
2 AU	3 hours	30 hours	6 days	11.4 days
3 AU	4.5 hours	42 hours	8.6 days	16.5 days
4 AU	5.5 hours	54 hours	11 days	21.2 days

With these initial bounding results, a simulation could then be built in the Optical Navigation Program developed by NSA JPL.

SIMULATION

Software Package

Since the measurements being used in this study are all optical based measurements, it was decided that the Optical Navigation Program (ONP) would be used. Along with an extensive amount of heritage, having been used on Voyager and Mariner missions all the way up to present day missions, ONP does not fall under ITAR restrictions such as MONTE.

ONP is a powerful navigation software package that can predict image locations, produce plots of expected images, compute residuals, generate partial derivatives (analytically, not numerically), perform a camera pointing solution, and compute target error ellipses resulting from an OD solution.[9]

ONP consists of three main programs that work together to produce results.

- Trajectory Geometry Program (TGP) - Picture prediction tool that takes the input parameters and produces the required inputs for OOPG to produce simulation pictures.

- Optical Observables and Partials Generator (OOPG) - Analyzes observations before the filtering process.

- Optical Data Analysis Program (ODAP) - Filtering tool that produces the results and covariance analysis of the simulation.

Parameters and Results

Modification of the software was relatively straightforward as the time offset variable is a function of the velocity of the spacecraft and the celestial bodies used for the navigation solution. The formal 1-sigma uncertainty with a limited estimation set shows time recovery of 400-1500 seconds at a distance of 1 AU depending on the simulations pictures run through the filter. Table 3 shows the simulations that were run and the resulting uncertainties. The best case scenario is taking a picture set of Jupiter, Saturn and Mars over the course of 7 days with 120 simulation pictures input into the filter. Error was added to the filter in the form of random white noise and a ½ pixel error on objects in the field of view. All simulations were run with the Sinclair star tracker as the baseline.

Table 3 shows a sample of the different picture sequences that were run through ONP and the results that were obtained. This was done with the spacecraft having a 12 hour offset from the true time and allowing the filter to correct for the time after the batch filter was run with the data. The numbers in the table correspond to the following picture sequence.

1. 3 days. 3x pictures each day. Total of 9 pictures
2. 7 days. 3x pictures each day. Total of 21 pictures
3. 30 days. 3x pictures each day. Total of 90 pictures
4. 7 days. 3x pictures every 4 hours. Total of 120 photos

Table 3: Filter Uncertainty versus Picture Sequence

Picture Sequence	Filter Uncertainty (Secs)	Corrected Time (Secs)	Corrected Time (Hours)	Offset from 12 hours (Secs)
(1)	1544	75248	20.90	32049
(2)	892	46964	13.05	3765
(3)	482	42170	11.71	1030
(4)	418	43703	12.14	503

Table 3 shows that with 120 observations time can be resolved down to 500 seconds from the initial 43,200 seconds (12 hours) offset presented to the spacecraft.

CONCLUSION

Future Work

It is clear that the more observations that are used, the better the simulation results are. Studies will continue to be run that explore the trade space of taking pictures in quicker succession over short time spans to see the results that can be obtained.

Further works past this will be working to complete an entire simulation framework that can solve for position and velocity once time is solved for. This current solution uses the saved data from the spacecraft to solve for the correction of the 12 hour offset. As the offset is increased, the a priori data will become less useful and initial position data will have to be accumulated.

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