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[SSC20-WKVI-03]

The First Solution to the Lost in Space Problem

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ABSTRACT

In December 2018 and January 2019, weeks after a successful fly-by of Mars and relay of the InSight landing, communication with the MarCO cubsats were lost. The causes of this loss of communications with the MarCO cubesats are unknown, but could be related to a power issue or onboard fault. This leaves the MarCO cubesats effectively, lost in space, having no way to autonomously recover time, position, or velocity, should the spacecraft recover from the anomaly.

This research will show a full solution to the lost in space orbit determination problem. This solution is achieved by using self-acquired optical observations via cubesat star tracker, of the planets, moons, and stars, thereby re-initializing the mission operations using low size, weight and power sensors compatible with small spacecraft architecture.

Such cases of a lost in space spacecraft have not been systematically investigated until now. This research will show that it is indeed possible to solve this problem, recovering time, position, and velocity, and will show analysis in the context of the high precision requirements of planetary missions. Using the MarCO architecture and hardware as a baseline, this research will present a solution based on the orbital parameters of the MarCO cubesats.

INTRODUCTION

As small spacecraft, push the bounds of deep space, it is expected that there will be more anomalies as adjustments are made to allow small spacecraft to survive in this new environment. In December 2018 and January 2019, weeks after a successful fly-by of Mars and relay of the InSight landing, communication with the MarCO cubsats were lost.[1] A relative location of the MarCO cubesats in relationship to Mars, Jupiter, and Saturn are shown in Figure 1. Should the MarCO cubesats recover, they will be without time, position, or velocity information, thus making them, lost in space and unable to communicate with Earth as they will have no knowledge of the location of Earth.

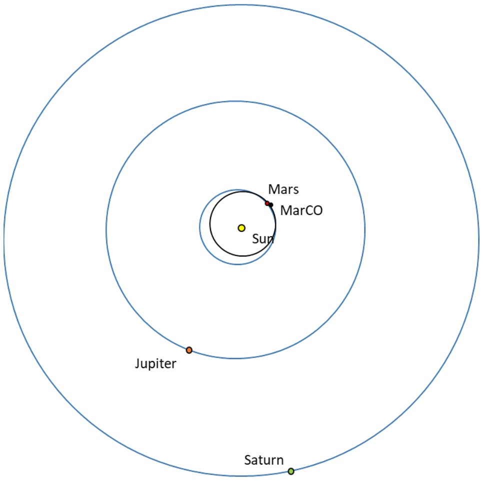


Figure 1: Location of MarCO cubesats when communication was lost December 2018.

Being able to quickly and autonomously recover time, position, and velocity from an environment with no Earth contact will advance mission safety and automation from current methods which require an Earth contact. This solution adds robustness and enhanced fault-to-recovery capability to deep space cubesat architecture without any expensive specialized hardware solutions. This solution opens up the realm of possible space missions for cubesats, helping to alleviate deep space communication resources by allowing navigation of the spacecraft to be entirely self-contained on the spacecraft, including initialization of the spacecraft state.

For context on the foundation of this problem, and previous research to reach this point, please refer to the paper from SmallSat 2019.[2]

APPROACH

Based on the best available hardware for small satellites, optical measurements from star trackers are used to solve for the lost-in-space problem. The most important factors when determining a viable star tracker include focal length of the optics and the pixel to area ratio of the detector. Based on these factors, the Sinclair CubeSat star tracker is selected, as it is capable of resolving Jupiter and the Galilean moons from a distance of 10 AU. Additionally, the Sinclair star tracker has a focal length of 16 mm, 1944 x 2592 pixel detector, with each pixel measuring 2.2 µm, and sensor physical dimensions of 7.13 mm across the diagonal.[3] The Sinclair star tracker also has available specifications online and has similar properties to the Blue Canyon star tracker on the MarCO cubesats.[4]

The approach selected herein is to recover time for the lost-in-space problem using Jupiter, Saturn, Mars, and the Galilean moons in the Jovian system. Since Jupiter, Saturn, and Mars are bright objects, they are easily detected with current CubeSat star tracker technology. Solving for position and velocity without time yields a relative solution, which, with the periodicity of the planets, could produce that exact same scenario at a future or past time. For example, both Jupiter and Saturn are on a 60 year orbital cycle because of a 5:2 near-resonance, which means that a position and velocity solution of a spacecraft with respect to Jupiter and Saturn will be the same in the year 2000 as it will in 2060. This shows that solving for time is vital for an absolute solution to the lost-in-space problem. For applications that rely on communication, it is imperative that an absolute solution be determined, as a solution relative to Jupiter is not sufficient to determine how to point the spacecraft to communicate with Earth.

The proposed solution assumes a satellite that has awoken from a cold state with only the last saved knowledge of time and state. This approach would also require that a catalog of stars and planetary ephemerides are loaded on the spacecraft prior to launch and is 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 be in error. However, with a prior state vector available, the navigation system would be able to bound the problem to the last possible known time and known trajectory, thus decreasing the extent of the feasible solution space that must be explored to determine the current time.

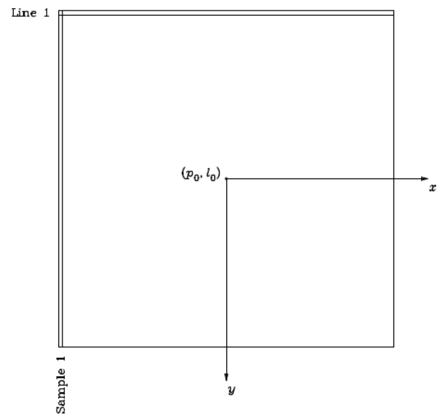
Since the measurements being used in this study are all optical based measurements, it was decided that the JPL Optical Navigation Program (ONP) would be used. Along with extensive heritage, having been used on the Voyager missions all the way up to present day missions, ONP had the necessary tools such as filtering and optical prediction already developed and verified.[5,6] The Optical Navigation Group at the Jet Propulsion Laboratory (JPL) maintains the ONP as part of the multimission program set. ONP is a powerful navigation software package that can predict image locations, produce plots of expected images, compute residuals, generate partial derivatives, perform camera pointing solutions, and compute target errors resulting from an OD solution.[7]

Algorithm

The algorithm developed for implementation into ONP is as follows,

$$\begin{pmatrix} p_t \\ l_t \end{pmatrix} = \boldsymbol{K} \frac{f}{\rho_{t3}} \begin{pmatrix} \rho'_{t1} \\ \rho'_{t2} \end{pmatrix} \tag{1}$$

Where p_t l_t are the image observable (sample (pixel), line), as shown in Figure 2, f is the focal length, K is a matrix averaged to a single constant that describes the physical layout of the pixels within the focal plane, and ρ'_{t1} ρ'_{t2} ρ_{t3} are the vector components of the position difference between the planetary target and spacecraft.



Equation 1 represents the predicted locations of objects relative to the observer that ONP uses to create accurate pictures in the simulation. Equation 1 is then differentiated with respect to time to yield,

$$\begin{pmatrix}\dot{p}_t\\ \dot{l}_t\end{pmatrix} = \boldsymbol{K}\frac{f}{\rho_{t3}}\begin{pmatrix}\dot{\rho}'_{t1}\\ \dot{\rho}'_{t2}\end{pmatrix} - \frac{f}{\rho_{t3}^2}\begin{pmatrix}\rho'_{t1}\\ \rho'_{t2}\end{pmatrix}\dot{\rho}'_{t3} \tag{2}$$

Where $\dot{p}_t\ \dot{l}_t$ are the image observable derivative (sample (pixel), line), and $\dot{\rho}'_{t1}\ \dot{\rho}'_{t2}\ \ \dot{\rho}'_{t3}$ are the vector components of the position difference time derivative between the planetary target and spacecraft. This is the equation that can now be used to estimate the spacecraft location by comparing the actual observed data to an ephemeris, essentially comparing the simulated location of the object, and relative velocity compared to the spacecraft, to the expected location. Doing this comparison with only one object would not yield enough information to solve the problem, which is why multiple must be used. This yields a difference from the truth state that can then be iterated on in a batch processor to converge on the correct state.

Parameters and Results

To setup the simulation, the truth state for the MarCO cubesats was set to be December 6th, 2019, one year after the lost contact. This is shown in Figure 2.

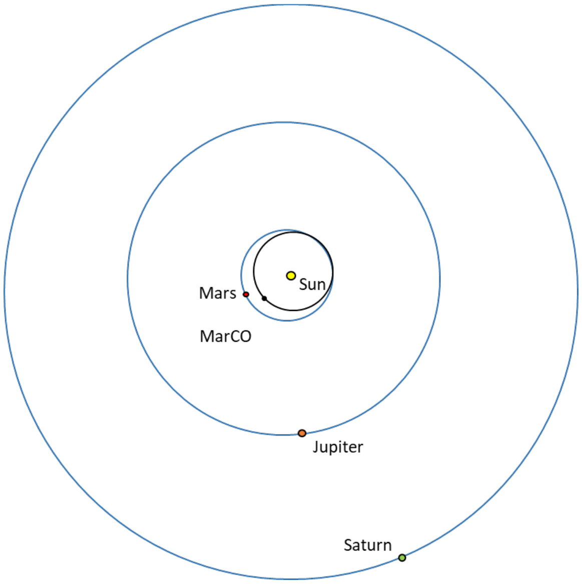


Figure 2: Location of MarCO cubesats on December 2019 in relationship to Mars, Jupiter, and Saturn.

A picture sequence was used that took images for a 12-hour period of Mars, Jupiter, the Galilean moons, and Saturn every hour, as shown in Table 1. In a comparison study, this sequence showed to have a good balance between time to recovery, and accuracy of the final state. The results of a comparison study are not presented in this paper.

Table 1: Truth state versus initial guess for the MarCO cubesat in Sun-centered coordinates

Time	Picture Sequence
00:01	60 images of Jupiter and Galilean Moons on 1 second interval
00:03	60 images of Saturn on 1 second interval
00:05	60 images of Mars on 1 second interval
01:01	60 images of Jupiter and Galilean Moons on 1 second interval
01:03	60 images of Saturn on 1 second interval
01:05	60 images of Mars on 1 second interval
	Same sequence continued every hour
11:01	60 images of Jupiter and Galilean Moons on 1 second interval
11:03	60 images of Saturn on 1 second interval
11:05	60 images of Mars on 1 second interval

Table 2 shows the truth state of the MarCO cubesat on December 6th, 2019 and an initial guess that was chosen based on time parameters laid out in the paper from SmallSat 2019.[2] The velocity guess is placed at 0 to simulate the spacecraft with no initial pictures taken to obtain velocity knowledge from. Position is estimated based on an irradiance measurement from a sun sensor or solar panels.

Table 2: Truth state versus initial guess for the MarCO cubesat in Sun-centered coordinates

	Truth State	Initial Guess	
X	**-1.42823825380E+08**	**-1.40619397379E+08**	**km**
Y	**-1.00973667000E+08**	**-9.94151792738E+07**	**km**
Z	**-4.19482277781E+07**	**-4.13007738420E+07**	**km**
DX	**2.01854530013E+01**	**0.00000000000E+00**	**km/s**
DY	**-1.84723319180E+01**	**0.00000000000E+00**	**km/s**
DZ	**-8.74699330982E+00**	**0.00000000000E+00**	**km/s**
Time	**Dec 06 2019 00:00:00.00**	**Nov 30 2019 00:00:0.00**	

The simulation was run through five batch iterations before converging on a final solution. The first three iterations were run without taking into consideration the Galilean moons. This was because with a large initial time offset based on the initial guess, the small periodicity of the Galilean moons can cause a convergence on an incorrect solution. This is remedied by running a batch simulation until the current answer is within a settable tolerance from the previous batch answer, and then adding in the Galilean moons for consideration through the filter. Since the same pictures are used for each batch, it is simple enough to just exclude them from filter consideration.

Once the filter converged on an initial solution after the first three iterations, the Galilean moons were added back into consideration for iterations 4 and 5. The results of the last iterations are shown in Table 3 with the final difference and uncertainty given in Table 4.

Table 3: Truth state versus final estimated state for the MarCO cubesat in Sun-centered coordinates

	Truth State	Initial Guess	
X	**-1.42823825380E+08**	**-1.42824513720E+08**	**km**
Y	**-1.00973667000E+08**	**-1.00973936110E+08**	**km**
Z	**-4.19482277781E+07**	**-4.19486056380E+07**	**km**
DX	**2.01854530013E+01**	**2.02060971720E+01**	**km/s**
DY	**-1.84723319180E+01**	**-1.84773658570E+01**	**km/s**
DZ	**-8.74699330982E+00**	**-8.74710930260E+00**	**km/s**
Time	**Dec 06 2019 00:00:00.00**	**Dec 06 2019 00:00:10.75**	

The

Table 4: Difference and final uncertainty after 5 batch iterations

Difference	Final Uncertainty	
688.33970	**977.10**	**km**
269.10965	**280.87**	**km**
377.85990	**196.33**	**km**
-20.64	**7.85**	**m/s**
5.03	**2.17**	**m/s**
0.12	**1.58**	**m/s**
10.75	**59.26**	**s**

CONCLUSION

From table 4, final convergence shows that the simulation is able to solve for position vectors that are 1000 km from the truth position and velocity components that are each below .05 km/s. The X and Y position vector components and Z velocity vector component fall under the filter uncertainties but there may be a small non-linearity in the X and Y velocity components due to noise or an under-observability. Time was able to be solved for within 11 seconds of the true time state. This under observability can be rectified by taking more observations during the 12-hour picture sequence or extending the picture sequence beyond 12 hours.

With the results of the simulation, the MarCO cubesats would have been able to locate Earth to communicate with, even though visually they would not have been able to see the Earth as it was in the keep out area for the star tracker in relationship to the Sun, as shown in Figure 3.

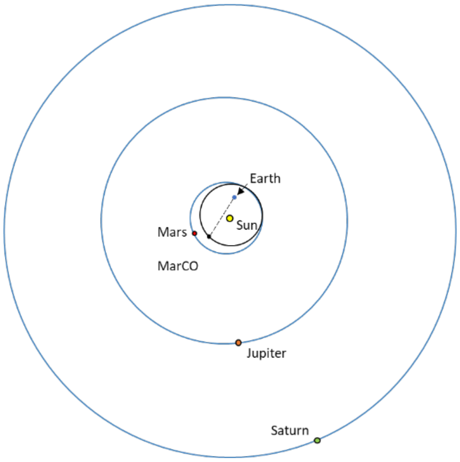


Figure 3: Final location of the Marco cubesats in relationship to Earth showing Earth in the keep out area for the Sun in order for the star tracker to observe.

Future Work

With a solution for the lost in space problem in hand and successfully applied to a cubesat platform, this solution should be able to be directly applied to a larger spacecraft platform with the expectation that results will scale in relationship to the optical performance ability onboard the spacecraft.

This solution can also be applied to spacecraft located in an Earth orbit as a way to add robustness in time to recovery for faulted systems. The solution space able to be solved for may only be on the order of hours, as opposed to weeks for deep space spacecraft because of the periodicity of the spacecraft orbit around Earth, but the addition of a lunar trade space would aid in perfecting a solution.

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