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Autonomous navigation methods for spacecraft formation flying in cislunar space

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Abstract – Due to the increasing number of deep space missions in the following years, the focus on methods and strategies that enable a spacecraft to perform critical operations autonomously is becoming crucial. In the context of cislunar space, this research aims to investigate state estimation methods for such a highly nonlinear dynamics environment in order to identify the best operational scenarios and constraints that enable accurate performance for autonomous spacecraft navigation. In particular, the LiAISON navigation method is considered in the context of a formation of satellites moving in cislunar space exploiting the presence of other cooperative satellites to exchange inter-satellite signals to get range measurements.

Introduction

In the context of current and future lunar missions, the number of operating satellites in the cislunar environment is expected to grow. At the same time, spacecraft formation flying (SFF) is receiving increasing attention for its concept of distributing the functionality of a single spacecraft between several close-flying satellites, and for its higher adaptability and flexibility to different mission concepts. For these missions, the baseline option for orbit determination is, in general, ground-based radiometric navigation. Through technological advancements in autonomous Guidance, Navigation, and Control (GNC) capabilities for formation flying two main benefits would be accomplished: reduced costs and ground operations, and superior performance in terms of control accuracy and mission adaptability. For these reasons, autonomous navigation methods for SFF operating in highly nonlinear dynamics environments are investigated.

Space missions of formation of satellites in regions far from Earth pose different challenges for navigation and communication due to large distances. Nowadays, spacecraft navigation techniques for deep-space missions largely rely on radiometric measurements collected on the ground by the Deep Space Network (DSN). All data are processed on the ground to estimate trajectories and plan maneuvers. Newman et al. [1] have assessed the extent to which the DSN should be utilized to meet the tracking requirements for orbit determination. As a reference, for the Lunar Gateway, in the absence of any onboard sensors, DSN measurements should be used at least three contacts per orbital period, lasting 6 hours each time, to meet the navigation performance requirements [2].

There are several challenges to navigating in cislunar space that the current ground-based navigation paradigm does not readily address, such as their limited scheduling resources due to the increasing number of deep-space missions, constrained observation times, processing time and communication delays [3]. For these reasons, the concept of autonomous navigation is gaining interest as the most favorable approach for lunar missions.

Current Trends for Navigation

In the last decade, the first idea to alleviate the load of ground stations was still to assume the DSN as the primary resource for providing inertial measurements, but with the reduction of its overall work through the utilization of different onboard sensors. Secondly, with the ultimate goal of a completely autonomous system, the problem where a satellite attempts to simultaneously estimate its own inertial state, as well as the inertial state of a target with only relative measurements, was considered. This so-called co-estimation problem was first solved using cross-linked range measurements within the Linked Autonomous Interplanetary Satellite Orbit Navigation (LiAISON) method [4]. Then, newer works expanded LiAISON results to optical measurements [5], and different sensors have been considered within the concept of data fusion [3,6,7,8]. Among them, X-ray pulsar navigation and, most importantly, cameras for optical navigation have been considered to get measurements from observations of asteroids, other satellites, Moon centers, and landmarks.

Regarding fully autonomous navigation strategies, current research interests focus on two main trends. The first relies solely on optical navigation, showing that the most efficacious target observations are images of artificial satellites and observations of the Moon (landmarks and/or the center of the figure). The second trend relies solely on satellite-to-satellite measurements, such as range or range-rate. These two systems differ in the algorithms used to process the sensor output and in the power consumption and weight of the overall equipment. Both of them rely on the concepts of the LiAISON navigation method.

LiAISON navigation is based on the notion of uniqueness. If there exists an orbit that is unique, then its absolute orientation is spatially unambiguous, and therefore any other orbit measured with respect to that orbit will, likewise, also be unambiguous. The characteristics of the acceleration function determine whether a unique trajectory exists, and also the degree to which the absolute position of the spacecraft can be estimated using inter-satellite measurements. Building on this assertion, satellites that are in sufficiently distinguishable orbits, are most attractive for this type of navigation. Fortunately, for spacecraft orbiting in the Earth-Moon neighborhood, the three-body dynamics provide the appropriate conditions for unique trajectories and for the subsequent use of such an autonomous navigation system. The LiAISON technique cannot determine the absolute states of both satellites from a single epoch measurement; rather, it requires a time series of measurements that are long enough for the asymmetric dynamic effects to show up in the data.

First Results

Simulations of hybrid strategies (implementing autonomous navigation methods but still relying on DSN) have shown, as a first remarkable result, the possibility of reducing the workload of DSN and ground operations in general, such as data processing and subsequent satellite uplink. In their work, Yun et al. [7] have shown how the combined use of optical navigation, antennas for GPS, and X-ray pulsar navigation could reduce the dependency on DSN to one hour per pass, a six-fold reduction from the nominal DSN-only approach.

Bradley et al. [3] support the feasibility of autonomous navigation in cislunar space with current technology and the application of LiAISON. They have demonstrated the possibility of meeting different navigation performance requirements based on the ability of three optical cameras with different resolutions to extract information from various target types at different times. The results show average uncertainty levels ranging from tens of kilometers to single kilometers. The more targets in visibility and the more measurements that can be provided to the navigation filter, the more accurate the state estimation will be. The most useful target types turn out to be artificial satellites and lunar centers. In particular, different mission scenarios, including different data cadences and correction maneuvers within the time windows of the estimation process, have been analyzed to also consider the robustness of the filtering process with respect to these aspects.

Following this work, Greaves and Scheeres [9] underline that all the previous work assumed a well-known target state so that only a relative state needed to be estimated. Therefore, they state that performing autonomous navigation using just optical sensors is possible, but they also put in evidence that the range estimate generated using bearing measurements is often only weakly observable and highly dependent on the nominal trajectory. For this reason, they have explored new guidance policies, which seek to maximize range information in the cislunar co-estimation problem given relative optical measurements. This has been investigated for the idea of performing autonomous navigation in cislunar space by exploiting targets whose state has to be estimated as well.

Based on the concept of co-estimation with a target satellite, autonomous navigation performed using crosslink radiometric measurements such as range and range-rate is investigated in recent works [10,11,12,13]. Firstly, the authors have shown that range measurements in general provide better state estimation than range-rate observations for cislunar satellites performing autonomous navigation. Then, they have shown that the LiAISON technique could be a possible approach for the LUMIO mission, based on the existing inter-satellite link with the Lunar Pathfinder satellite without using any ground-based measurements. By means of an observation effectiveness analysis, they have also highlighted the presence of optimal tracking windows, which is a crucial remark considering the goal of optimizing the onboard measurement schedule. The same authors have then focused on the analysis of radiometric navigation for cislunar satellite networks involving three satellites moving in centralized or distributed configuration by exploiting the existing communication links between them. The distributed topology has been found to provide better state estimation and quicker convergent navigation solutions.

Regarding these feasibility analyses involving LiAISON navigation, the authors have underlined the importance to investigate what would happen considering the full operative mission lifetime and the presence of dynamics errors and clock model errors. To consider the practical challenges of implementing LiAISON, Wang et al. [14] developed a high-fidelity model to consider the effects of model errors and time synchronization on navigation performances. The most relevant conclusion drawn from this work is that LiAISON navigation allows to meet quite accurate navigation performances even considering a high-fidelity dynamic model. This has been possible by considering these model errors within the navigation filter algorithm. The authors have finally underlined several times the strong dependence of the estimate accuracy on the measurement geometry, which leads to very different performances to be evaluated according to mission requirements. In other words, the orbital regimes of the satellites involved in the navigation scenario strongly influence the resulting performances.

Summarizing the current trends for autonomous navigation in cislunar space, the Cislunar Autonomous Positioning System Technology, Operations, and Navigation Experiment (CAPSTONE) mission will serve as a pathfinder for navigation and operations in the same near rectilinear halo orbit (NRHO) that will be utilized by NASA’s Lunar Gateway [15]. The Cislunar Autonomous Positioning System (CAPS), a navigation product developed by Advanced Space via a NASA Small Business Innovation Research, is intended to allow for the navigation of most small satellites without the requirement of a high-gain antenna, high-sensitivity GNSS receiver, or other specialized onboard hardware [16]. While standard DSN two-way navigation will still be the baseline operational navigation framework for the mission, the ultimate goal is to demonstrate navigation with either no ground-in-the-loop or without a dedicated two-way ground link. Currently, there are two measurement paradigms that can be processed by the CAPS flight software: crosslink measurements between two spacecraft, and one-way uplink measurements made possible by an onboard Microsemi SA.45s chipscale atomic clock (CSAC), which will leverage the enhanced oscillator stability for the estimation of clock bias and drift within the navigation filter.

To demonstrate the expected performance of CAPSTONE, high-fidelity navigation simulations have been performed considering noise values and biases that are expected based on ground tests of mission hardware. According to these preliminary results, one-way measurements or crosslink measurements alone would likely be good enough to support the onboard planning of orbit maintenance maneuvers if desired. Each of these data types can provide onboard solutions comparable to the quality of the ground-based filters given the expected CAPSTONE tracking schedule. Additionally, the utilization of both data types can provide additional improvements to onboard solutions. The scientific community look forward to analyze CAPSTONE's experimental data, and sharing the achieved results with the rest of the world.

Spacecraft Formation Flying Navigation

The aforementioned navigation problem focuses on single spacecraft missions interacting with already present targets in cislunar space, but, considering the presence of close-flying satellites within the concept of SFF, relative navigation issues must be addressed as well. Considering the problem of autonomous relative navigation between an active satellite (chaser) and another space object (target) orbiting in close-proximity, for SFF applications the latter can be included in the category of actively or passively cooperative targets, depending on the strategy adopted. In the actively cooperative target case, both chaser and target have the knowledge of their own state with a certain degree of uncertainty and they exchange information by means of a communication link. In some cases, the target may also be cooperating in a passive way, through artificial markers on the spacecraft body that can be detected and tracked by the chaser spacecraft.

In general, the state estimation problem for SFF has attracted a considerable amount of attention due to its practical and theoretical significance. The most direct and accurate way to solve this problem is to design centralized solutions, in which the chief performs all the computation for the fleet using data collected from the deputies [17]. Unfortunately, as the number of the spacecraft information becomes larger, the computation burden of the chief becomes unbearable due to its requirement of large state covariance and measurement matrix calculation [18]. To overcome this problem, decentralized solutions are designed, which allocates the computational load among all the spacecrafts in the formation by gathering the measurements and estimating the state in a decentralized way (i.e. each spacecraft gathers its own measurements and has its own estimator) [19].

Navigation Filters

Following the guidelines given by Pesce [20], some relevant aspects have to be taken into account while designing a navigation filter. It must be robust to measurements and initialization errors. This implies that an appropriate filter should converge to the desired solution in a reasonable time and with an opportune accuracy, also in the case of measurement noise levels and uncertainty in the dynamical model different from the expected ones. The computational load must be reduced due to the fact that high frequencies can be required but the computational power onboard is limited. As importantly, the choice of the model to describe the state dynamics is crucial for filter design. External disturbances and orbital perturbations could be included, implying an increase of the computational cost, but they are necessary for filters with low frequency updates or long operational time, when the effects of perturbations become significant, like in the case of SFF.

An efficient way to handle the prediction step of a Kalman filter, including an accurate dynamic model to propagate covariance and trajectory, is a relevant topic nowadays with the aim of improving the accuracy of the filter without affecting computational performance. The specific case of navigating in cislunar space turns the attention towards the problem of state estimation in the context of highly nonlinear dynamics. In addition, for autonomous purposes, current researches focus on the use of sequential filtering that allows for the simulation of an actual real-time onboard implementation. In particular, the extended Kalman filter (EKF) and the unscented Kalman filter (UKF) are widely used. Regarding EKF, in some cases, the linear assumption fails to provide an accurate realization of the local trajectory motion due to the low frequency of the estimation process as well as the nature or the limited number of measurements. In such cases, UKF yields superior performance in highly nonlinear situations because it is based on the unscented transformation, which does not contain any linearization. Following the idea of enhancing the filter's ability to manage nonlinear dynamics, in the work of Valli et al. [21], it has been demonstrated that working in the differential algebra framework significantly reduces the complexity and the computational burden related to the standard higher-order approaches.

Additionally, in the context of using the LiAISON strategy, the same nonlinearities that produce observability also cause issues for linearized filters. The filter linearization assumptions are further strained by the inflated uncertainty profiles associated with the co-estimation problem. Thus, it becomes increasingly vital to obtain additional state information and to manage the prediction step better to alleviate nonlinearities, improve observability, and ensure accurate navigation.

Conclusions and Future Perspectives

The main focus of this research concerns the role of the navigation filter for the autonomous navigation of a formation of satellites operating in cislunar space. At the same time, the idea is to evaluate the navigation performance by considering combined metrics that take into account both estimation accuracy and mission objectives in order to consider a practical use of the algorithms and the possible improvements to realistic applications.

The major part of this research regards how to manage state estimation in such highly nonlinear dynamics, understand the behavior of propagated uncertainties, and how to mitigate their accumulation in a computationally efficient way. These points are addressed in the context of autonomous navigation, considering a possible real-time onboard implementation according to appropriate mission limitations and requirements.

To pursue these goals, the first step is the definition of accurate dynamic models and representative measurement models. In a navigation framework including the LiAISON method in the three-body problem of the earth-moon system, the satellites involved can operate in orbital regimes experiencing very different acceleration fields. For a practical implementation of the desired strategy, it is fundamental to consider dynamic model errors and clock errors. For the same reason, the actual sensors to be used onboard must be appropriately modeled considering real parameters and noise values. The most realistic dynamic environment should be reproduced through the implementation of a high-fidelity model of cislunar space, and an appropriate dynamic model must be included for the filter's prediction step considering computational constraints.

The effects of nonlinearity on the curvature of the state distribution after a certain propagation time could lead to an untreatable knowledge of the spacecraft state because of the accumulated uncertainty. For this reason, as a first step, this work aims to apply well-known uncertainty propagation techniques in order to analyze their behavior when used in the three-body dynamics with the ultimate goal of exploring strategies to mitigate their accumulation over time. Considering the peculiarities of such a navigation scenario, different state representations and uncertainty propagation techniques will be used within the prediction step of the estimation filter with the aim of defining a suitable strategy to meet requirements on the accuracy of the solution and computational load.

Additionally, considering the typical sparse observations of these navigation scenarios, and the need to speed up computations for efficient onboard implementation, the use of multi-fidelity propagation methods should be considered as a potential turning point. The choice to investigate the potential of these methods is also motivated by the different orbital regimes covered by the satellites involved in our scenario. This situation leads to the presence of time windows in which the model of the orbital dynamics could be simplified leading to a more performing propagation step.

Finally, considering formations of satellites flying at relatively short distances, the co-estimation problem results difficult to be solved [4]. For this reason, according to decentralized state estimation for SFF, the idea is to define a navigation strategy such that a leader satellite is involved in the solution of a co-estimation problem with appropriate external targets in cislunar space, while for the deputies the problem could be reduced to the sole estimation of the relative state through the use of RF-based or vision-based systems. The main goal is to investigate the effect of performing decentralized relative navigation with respect to a target whose state is retrieved in real-time through the LiAISON strategy.

Once the issues related to state estimation for SFF operating in this environment have been addressed, the idea is to recover the general framework of the desired mission to apply navigation strategies and methods to a practical test case. This research aims to put the navigation system of an SFF mission into the specific framework of a space mission, thus not just evaluating the state estimation performance in an ideal case without considering the actual mission requirements and onboard capabilities. The driven idea is to identify one or more specific surveillance missions in cislunar space for which SFF could provide benefits in terms of mission objectives. This will provide requirements on SFF orbit, sensor, configuration, and the number of satellites. Then, after a first simple evaluation of autonomous navigation performances, the idea is to define comprehensive metrics to combine the needs of guidance and navigation procedures with the objectives of a surveillance mission. The result is therefore to drive optimization procedures to identify guidance strategies to meet favorable navigation accuracy and surveillance performances. Finally, the potential role of SFF for other cislunar missions could be investigated.

Through the evaluation of the aforementioned metrics along one or more orbital periods or the entire mission lifetime, it is possible to highlight the presence of regions of space or time intervals in which the navigation strategy or the mission objective is not performing well. In this way, one can identify possible limitations of the considered mission and navigation strategy, but also use the metrics in order to drive some optimization routines toward more suitable solutions according to the desired requirements.

The final product of this process is to identify proper guidelines to improve the overall mission performance. The evaluation of the defined metrics could be used to identify appropriate solutions in terms of different aspects of the mission, such as orbital regime, target for the LiAISON strategy, type of sensors for surveillance operations, number of spacecraft and configuration for the formation.

To sum up, the following questions can be considered representative of the main objectives pursued by this research:

- Could an autonomous navigation strategy, based on the use of the LiAISON method and a relative navigation measurement system, lead to the required accuracy for SFF cislunar missions?
- Could the use of combined metrics for navigation and mission goals lead to the improvement of SFF mission design?
- Which are improvements resulting from the use of a multi-sensor configuration of satellites to perform surveillance operations of uncooperative targets in cislunar space?

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