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Low-thrust maneuver anomaly detection of a cooperative asset using publicly available orbital data

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Abstract. This work presents a novel method to estimate perturbations with respect to nominal maneuver planning by exploiting Two-Line-Element (TLE) data as initial step, then moving on to Global Positioning System (GPS) processed data. The case study is a low-thrust engine validation mission in Low Earth Orbit. The first algorithm exploits a couple of TLEs as boundary conditions to set up a least-squares problem and find the tangential thrust magnitude and firing duration to best fit the bounding orbital states, making use of Taylor differential algebra and Picard iterations. The second one makes use of a sequence of GPS states to apply multistep finite differences and a root-finding algorithm to retrieve information about both thrust profile and firing bounding times.

Introduction

Over the past few decades, there has been a steady growth in the quantity of scientific and commercial Earth-bound space missions. This upward trend has led to a significant expansion of activities and programs focused on Space Situational Awareness. Up-to-date orbital data obtained by updating ephemeris data with new observations play a vital role in effectively tracking cooperative target assets, offering valuable information to ensure a mission's success [1]. The main product provided by the processing pipelines used to exploit measurements' information are regularly maintained Resident Space Object catalogs [2].

The kind of anomaly detection performed in this framework is usually linked with the orbital motion of the satellite and to its routine maneuvers. The high-level workflow starts by exploiting available intel about known objects to build predictions of a target's nominal behavior and compare it to the actual incoming acquisitions. If any properly defined distance from the nominal path trespasses some user defined threshold, the anomalous event is recorded, and further analysis can be carried out. This specific case of anomaly identification widely overlaps with maneuver detection and characterization of a tracked object. The reason for this is that according to how much it is known about the nominal trajectory and control policy of an object, any anomalous event involving the dynamics of the target can be modeled as a maneuver, steering it away from the nominal path, and characterized as such, in terms of an equivalent acceleration or expense. Examples in literature are diverse, most of them stemming from the theory of maneuver target tracking, dealing with observations that partially describe the state at observation epoch. These techniques are usually based on adaptive Kalman filtering modeling an input term as a stochastic process or a deterministic input to be estimated when the measurement innovation term fails a Gaussian test, meaning that the modeled uncertainty is no longer enough to explain deviations from the prediction [3]. As for a more SST-tailored application, the work in [4], shows how State Transition Matrix theory can be remodeled to linearly map small variations of control, modeled as an impulsive ΔV, to variations in the final orbital state. Following the usual optimal control assumption, the residual between the predicted final state and the actual one is minimized, linking the pre- and post-maneuver orbit with an impulsive magnitude and a firing epoch. This last method represents the basis for the one proposed in this work, allowing to connect two TLEs, by leveraging some assumptions based on the knowledge of the target features, by a high-order Taylor expansion of both thrust and firing epochs. As for the module exploiting GPS states, due to lack of rich literature, for the low-thrust case, a finite different method has been envisaged as first approach to test if an acceleration profile and accurate onset and termination times can be directly extracted from the states sequence.

Fundamentals and method

The theoretical tools used for the TLE-based maneuver anomaly detection are mainly Taylor Differential Algebra (DA) and Picard iterations, allowing for the condensation of iterative function evaluations in a single polynomial map, function of both thrust magnitude and time variations with respect to the reference onset and termination epochs.

DA provides a solution to analytical problems through an algebraic approach by means of the Taylor polynomial algebra. A Taylor expansion up to an arbitrary order k can be used to represent any deterministic function f of v variables that is C^{k+1} in the domain of interest $[-1,1]^v$ (scaled according to the needs), with limited computational effort:

$$f(x) = \sum_{k=0}^{N} \frac{f^{(k)}(x_0)}{k!}(x - x_0)^k \tag{1}$$

Thus, variables are represented as truncated power series around an expansion point x_0, instead of standard types [5]. The DA framework is implemented in a C + + computational environment through the DACE library. The key feature of DA leveraged for this technique is the flow expansion of an Ordinary Differential Equation (ODE): this feature relieves the processing burden due to iterative integrators embedding the whole integration scheme in a single function evaluation.

As for Picard iterations, they are implemented exploiting the same C++ computational environment following the scheme to obtain a k-order time expansion [6]:

$$\phi_0(t) = y_0 \tag{2}$$

$$\phi_{k+1}(t) = y_0 + \int_{t_0}^{t} f\big(s, \phi_k(\tau)\big)dk \tag{3}$$

Where $\phi_{k+1}(t)$ is the order k expansion, y_0 is the function value at the center of the expansion and f is ϕ function's time derivative expression, used to iteratively integrate around the reference time t_0.

As regards the GPS data-based technique, multi-step, high-order finite differences are used to provide an estimate of the acceleration and jerk directly from the velocity provided with the GPS states. The general formulation used to compose the coefficients involved in the differentiation scheme are derived from the Fronberg method reported in [7] to compute a 1-D derivative of arbitrarily high order on a uniformly spaced grid for a given number of points. To detect the onset and termination epochs of each firing instead, a thresholding method is employed, based on the variance computed on the cumulative sequence of data to detect abrupt changes in it, such as peaks or steps [8]. A final refinement step is performed to resolve the above-mentioned epochs below the sampling frequency of the given GPS states by exploiting a non-linear system root-finding algorithm (MATLAB fsolve) to put to zero the residuals corresponding to the first sampled GPS state downstream the discontinuities as a function of their corresponding epoch.

Concerning the method itself, the TLE-based module is based on several assumptions to limit the complexity of the problem: constant and tangential thrust during the firing, constant burning rate and known onset time. The process starts by propagating the state coming from the first TLE file by augmenting the state with thrust and mass and by using the nominally controlled trajectory as reference for the expansion. The number of firing arcs to be included between the TLE couple can vary, increasing the number of variables of the problem and, therefore, the number of possible solutions. The DA variables are initialized to order 4. They model the constant thrust norm perturbations of each firing arc together with its termination time, computed by 4 Picard iterations around the expected termination time. The process is repeated for every firing arc, composing TPSs mapping perturbations for each of them to the one on the orbital state. The process outputs a propagated final state used to build a residual with respect to the one derived from the second TLE file. This residual function is then fed to MATLAB fsolve so to find perturbations putting it to zero with limited computational effort. The firings' modeling process is summed up in Fig. 1.

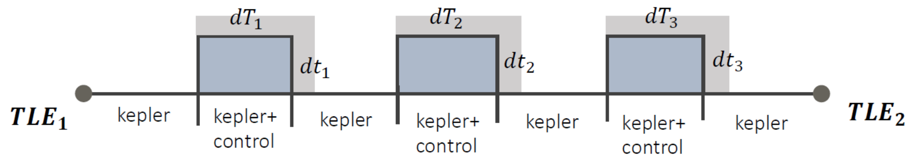

Figure 1. DA variables configuration for a 3-firing case, dT_n being thrust magnitude perturbations, dt_n termination time perturbations.

As for the GPS-based technique, the assumptions are two: the thrust is constant and tangential throughout the firing and so is the burning rate. It starts by simply computing the second time derivative of the velocity extracted from the sampled states. The norm of this quantity (jerk) is then employed to build residuals with respect to the second derivative norm of the expected trajectory velocity, computed by differencing only once, starting from the expression of the nominal dynamics. This sequence of residuals is scanned for abrupt changes by analyzing the variance computed on a progressively higher number of elements and checking whether it overcomes a predefined threshold.

Figure 2. Segments of data used to accurately differentiate the GPS velocity time series.

The discontinuity points identified are used to perform a composite finite difference method, splitting the time series of velocities into 7 segments for every arc, divided by the onset and termination times (as shown in Fig. 2). The method is composed of a backward finite differencing scheme of order 6 for the samples immediately before the discontinuities, a forward scheme of order 6 for the values just after it and a centered scheme of order 8 for the rest. In this way, a first estimate of the thrust profile can be obtained to give reliable boundary conditions to the boundary time estimates refinement. This last step is performed with a propagation across each discontinuity that is only a function of the related epoch. Residuals on the downstream state are defined and put to zero by MATLAB fsolve. Once the actual onset and termination times are obtained, the composite finite differencing scheme is performed once again with updated epochs and mass profile, and the final thrust estimate is retrieved.

Uncertainty propagation is embedded in both modules by means of linear projection of available covariances to the estimated quantities space (via the Jacobian of the transform).

Results

The scenario used to test the TLE-based module is simulated starting from a LEO object with the following Keplerian elements:

$$\boldsymbol{e} = [7.5805e+03\ km, 0.0760, 0.7151\ rad, 5.9935\ rad, 2.1723\ rad] \tag{4}$$

performing from 1 to 3 nominal firing arcs of 1100 s duration with a constant tangential thrust of 10 mN. The nominal trajectory is then perturbed with a 10 mN thrust parasitic magnitude and a 7 s firing termination time delay for the single firing case to generate the post-maneuver TLE. The same is done for the 2-firing (10 mN, 7 s for the first one, -7 mN, -3 s for the second one) and 3-firing cases (10 mN, 7 s, -7 mN, -3 s, -3 mN, 5 s). The tests show errors in below 1e-4 mN in thrust perturbation magnitude and 1e-5 s in termination time perturbation both in the 1 and the 2-firing cases, while the 3-firing one results in convergence to wrong local minima, due to solution multiplicity of the non-linear system.

As for the GPS-based module test scenario, the same target is involved and the thrust magnitude, onset and termination times perturbations are (4 mN thrust magnitude perturbation, -17 s onset perturbation, 35 s termination perturbation), used to sample the GPS states with a 5 s time step. In this case results show fair performance with 1e-1 mN as average error order of magnitude on thrust profile and errors of 1e-4 s for both onset and termination time perturbations.

Conclusions

This work presents a method to effectively exploit publicly available orbital data to perform maneuver anomaly detection on a cooperative asset. A crucial detail to understand the current performance of the technique resides in the fact that, due to the kind of preliminary study conducted on them to be then further elaborated, these first tests have been conducted without adding any noise to the states used as measurements. The first further step to take is in facts to study how sensitive these techniques are to measurement noise and whether to integrate the pipeline with filtering techniques to take this aspect into account and even it out.

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