Application of Efficient Uncertainty Propagation Methods in the Design and Analysis of Asteroid Missions

Iosto Fodde$^{1[0000-0002-7227-5922]}$, Jinglang Feng$^{1[0000-0003-0376-886X]}$, and
Massimiliano Vasile$^{1[0000-0001-8302-6465]}$

Department of Mechanical and Aerospace Engineering, University of Strathclyde, 75
Montrose Street, Glasgow, G1 1XJ, United Kingdom
`iosto.fodde@strath.ac.uk`

Over the last few decades, the exploration of asteroids have seen a steady increase in interest due to their scientific value and their potential of impact with Earth. One of the main difficulties of these types of missions, especially for missions aiming to orbit the body for long periods of time, is the highly non-linear dynamics, rising from their complex gravitational field, their spin state, and the relatively significant Solar radiation force present. Furthermore, the dynamical models are not well known beforehand due to the limited information available from remote sensing as the size of the body is generally too small to precisely determine the various parameters needed to accurately analyze the dynamics [4].

Previous work on the analysis of the motion of a spacecraft around an asteroid and the effects of uncertainties has often used simplifications of the dynamics and/or averaging and linearization techniques [5]. These approaches can give valuable insight into the dynamics but can become inaccurate when the dynamics are highly non-linear or the uncertainties are significantly large. On the contrary, numerical investigations using long-term propagation, e.g. [1] and [2], can be used with a higher fidelity dynamical model. These techniques analyse the evolution of the state variables for different initial conditions, and thus require long computation times. Furthermore, these numerical techniques focus on individual point propagations instead of producing analytical representations, which allow for a more in-depth analysis of the dynamics. Therefore, it is important to find efficient techniques that can provide dynamical insight through analytical models, while retaining the complex dynamical features present for motion around asteroids and allowing for the inclusion of uncertainties in the dynamics.

In this work, two uncertainty propagation techniques are discussed: the Generalised Intrusive Polynomial Algebra (GIPA) method, and the Non-Intrusive Chebyshev Interpolation (NCI) method. Both of these methods find a surrogate polynomial model of the uncertain dynamics, which allow for a more efficient analysis of the system. It is shown how these methods can be used in two different phases of an asteroid mission: the close-proximity orbiting phase, and the landing phase. For the close-proximity motion, two indicators are developed based on the polynomial coefficients from the GIPA method, which allow for the discovery of regions in phase space which are less sensitive to small perturbations in the state and dynamical uncertainties. Then, for the landing phase, both methods are used to find robust ballistic landing trajectories based on large scale searches of the possible maneuver space.

As a case study, ESA's Hera mission to binary asteroid Didymos is used. Hera aims to investigate the result of a kinetic impactor in more detail, in this case NASA's DART mission which impacted the smaller moon Dimorphos in late September 2022. This mission involves several CubeSats (Milani and Juventas) orbiting the system at close distances, ending with them attempting a landing on Dimorphos [3]. Hera is currently planning several long phases of early characterization to reduce the uncertainties coming from Earth based remote sensing of the system. Therefore, this work shows how these techniques can help in efficiently designing trajectories that are robust against these uncertainties, reducing the need and cost of these long characterization processes when arriving at the target asteroid.

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