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Rendezvous Involving a Non-Cooperative, Tumbling Target – Estimation of Moments of Inertia and Center of Mass of an Unknown Target

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Extended Abstract

In future on-orbit servicing missions, a service spacecraft approaches a non-cooperative, passive target spacecraft in its orbit to perform service tasks. These can comprise lifetime extensions tasks like takeover of orbit and attitude control, refueling, reparations, or space debris removal actions like safe deorbiting at the target spacecraft's end of life. The rendezvous and capture of the client spacecraft are critical phases in an on-orbit servicing mission. Concerning the rendezvous part, we face high challenges on guidance, navigation and control (GN&C).

A typical target satellite is neither equipped with reflectors or markers which can be used for relative navigation, nor has specially intended grasping/docking equipment for robotic capture. Furthermore, there is no communication between servicing and target satellite or between ground station and target. Therefore, the status of the target has to be assumed as fully unknown. This means that there is no information about the target's pose (position and orientation) and none about its inertia properties, which are necessary to propagate its state.

For a safe approach to and capture of the target, these inertia properties are important. For example, the motion of a possible grasping point on the target's side has to be propagated for planning a safe capture process. Further, having the target grasped, its motion has to be damped which is not possible without any knowledge of its inertia properties. Consequently, we have to determine the location of the center of mass of the body and its moments of inertia during a previous inspection phase carried out at a safe distance.

In the on-orbit servicing scenario, we need to make use of information which can be gained using the available equipment on the service satellite only. The target satellite is completely passive. Therefore, optical sensors such as cameras or LIDARs (LIght Detection And Ranging) mounted on the service spacecraft can be used. From a safe distance, the free-tumbling target satellite is observed and the inertia properties of the unknown target can be estimated using the sensor data.

Processing the data of optical sensors, the position of the center of some geometrical body frame of the target and its orientation can be measured. The center of mass may not match with the geometrical center. One task is to determine the shift between geometrical center and center of mass.

In this work, we assume that the target is freely rotating without any external torque acting on it. The center of mass and the moments of inertia are determined using kinematic equations and the conservation of angular momentum. As the angular momentum in an inertial reference frame is constant but unknown, it is estimated together with the inertia tensor. By employing several

measurements, we obtain an overdetermined linear system which can be interpreted in the least squares sense.

Additional to previous related work from literature, we take constraints on the moments of inertia into account to enforce positive entries in the inertia matrix. This induces a minimization problem with inequality constraints which can be solved using the active set method for convex quadratic programming. In addition, singular value decomposition of matrices is applied to overcome problems arising from numerical issues and measurement noise.

Furthermore, we consider special properties of optical sensors and their effect on tracking and observation. Our approach is therefore characterized by not only considering a pure mathematical optimization problem arising from the estimation problem, but also regarding practical issues and limitations during an inspection phase.

We finally demonstrate the developed methods for estimation of the inertia parameters on three examples. We investigate the accuracy and performance, the influence of the number of measurements, and analyze typical limitations in the observability of the quantities to be estimated. The observability is mainly dependent on the duration of the observation and the period of the rotational motion of the target.

In summing up, the objective of this paper is to estimate the center of mass and the moments of inertia of a non-cooperative, tumbling target using measurements of optical sensors mounted on the service satellite. The methods for estimating the inertia parameters are described in detail. Additionally to the main method, some improvements are presented and results from demonstrations and simulations are presented and discussed.