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Ground tests for vision based determination and control of formation flying spacecraft trajectories

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ABSTRACT

The advances in the computational capabilities and in the robustness of the dedicated algorithms are suggesting vision based techniques as a fundamental asset in performing space operations such as rendezvous, docking and on-orbit servicing. This paper discusses a vision based technique in a scenario where the chaser satellite must identify a non-cooperative target, and use visual information to estimate the relative kinematic state. A hardware-in-the-loop experiment is performed to test the possibility to perform a space rendezvous using the camera as a standalone sensor. This is accomplished using a dedicated test bed constituted by a dark room hosting a robotic manipulator. The camera is mounted on the end effector that moves replicating the satellite formation dynamics, including the control actions, which depend at each time step by the state estimation based on the visual algorithm, thus realizing a closed GNC loop.

1. Introduction

Visual based techniques have a long history in space missions. It is however in the last decade that these devices are getting more and more attention as standalone tools for orbital maneuvers. A major application can be seen in close proximity operations between two satellites (typically, a chaser and a target spacecraft), for operations like docking, rendezvous, and on orbit servicing. In particular, CNES (Centre National d'Études Spatiales) has implemented an on-board software for vision based navigation using two cameras accommodated on the chaser satellite, thanks to its participation in the PRISMA mission [1]. In this experiment the target satellite must be considered as a cooperative member of the formation of satellites: in fact, the Close Range Camera designed to estimate the relative attitude and position of the target satellite (Tango) was based on the extraction of Light Emitting Diode patterns purposely mounted on the spacecraft. In this paper we consider instead the case of a completely non-cooperative target, which has to be identified and characterized in terms of relative position and orientation. This problem can present different levels of difficulty, depending on the scenario considered. In fact, a spacecraft on the dark background of the outer space is an easily detectable target, while a more complex situation happens when the Earth or the Sun enters the chaser's camera field of view. Even more complicated situations arise when a particular zone of the target's external structure must be identified to be approached for operations like grasping or docking. In this work, an image identification algorithm, the Scale-Invariant Feature Transform [2,3] will be described and adopted to face these problems. Once the target spacecraft is precisely identified, the estimate of the complete relative state (position and velocity) is performed by means of a Kalman filter, based on the measurement coming from the visual identification process. The approach can be investigated by means of an experimental replica of the orbital scenario. Different strategies can be followed at the

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scope of testing on ground space navigation and control systems. Free floating, unwired, platforms were presented for example in [4,5]. Instead, DLR (Deutsche Zentrum für Luft- und Raumfahrt) has established a test facility [6] called European Proximity Operations Simulator (EPOS) which is a highly accurate testbed for rendezvous and docking simulation under realistic conditions as they occur in space. The DLR mechanism is constituted by a robotic arm moving the chaser satellite, where a vision-based sensor (monocular camera) is used for relative navigation. At University of Würzburg [7], a similar manipulator is used to test a PMD (Photonic Mixer Device), a Time of Flight based 3D imaging sensor, for relative motion estimation of a spacecraft like target.

Also in this work the robotic manipulator approach is used, but it refers to larger space relative dynamics (i.e., a smaller scale factor exists between experiment and actual maneuver). A dark room (approximating the space conditions from a visual point of view) has been realized in the Guidance and Navigation Laboratory at Università di Roma La Sapienza, as a testbed for spacecraft formation dynamics. A target satellite is positioned in a reference point (which is assumed as the origin of the orbiting reference frame), while a chaser satellite orbits in close proximity of the target satellite thanks to a robotic arm (already described in [8]), that moves according to the orbital laws. The camera, representing the chaser, is accommodated on the end effector of the robotic arm. This testbed implements a hardware-in-the-loop configuration, where at each time step the relative state estimate, evaluated from the visual information, is used to compute the control actions, that successively moves the robotic arm. Experimental evidence will show the performance and the limits of the proposed approach for the use of visual based techniques as a standalone tool (or as a back-up solution when other sensors fail) for close proximity operations such as rendezvous.

2. Mission scenario

The modeled scenario envisages that the chaser satellite has completed a preliminary approach phase, and it is now in proximity of the target satellite, along a closed relative trajectory [9] (a 30 × 15 m^2 in-plane elliptic relative orbit, centered 30 m away from the target satellite). This could be considered an intermediate configuration before completing the rendezvous operations. In Fig. 1 the relative trajectory is plotted, in the Local Vertical Local Horizontal frame (LVLH), centered at the target satellite position.

In the proposed scenario, the chaser satellite determines its relative state by means of the camera, used as a standalone instrument, and it completes the rendezvous relying on the estimates of the relative state coming from the visual device. To this aim, it is supposed that the attitude of the chaser spacecraft is kept constant with respect to the y direction of the LVLH frame, so that the target satellite is always in the chaser's field of view Fig. 1). In other words, the chaser's attitude is fixed in the orbital frame. Also the target's attitude is considered stationary in the orbital frame, therefore actually only the relative position has to be estimated. Once the estimates of the relative state converge to the real value, the rendezvous maneuver starts, so that the chaser satellite tracks the desired relative state with respect to the target satellite.

3. The experimental testbed

The testbed used for the experiments is based on a dark room where an articulated arm replicates the formation dynamics Fig. 2. Currently, only a two-dimensional motion is realized, thanks to a planar, three links (lengths 58, 24, 6 cm) manipulator with a camera mounted on the end-effector. During the tests, the formation orbital dynamics is

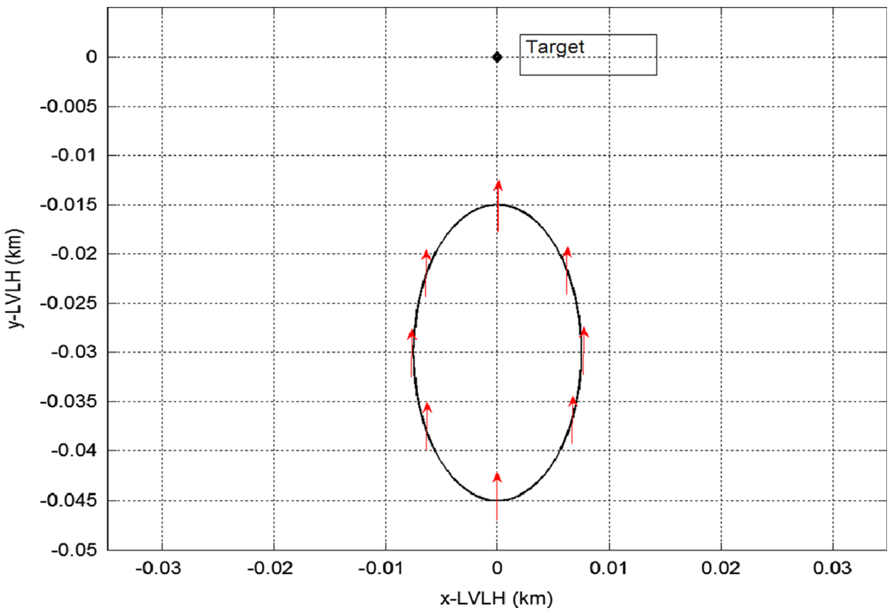

Fig. 1. Parking orbit of the chaser in an orbital reference frame attached to the target.