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Vision-based localization for on-orbit servicing of a partially cooperative satellite

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ABSTRACT

This paper proposes ground-in-the-loop, model-based visual localization system based on transmitted images to ground, to aid rendezvous and docking maneuvers between a servicer and a target satellite. In particular, we assume to deal with a partially cooperative target, i.e. passive and without fiducial markers, but supposed at least to keep a controlled attitude, up to small fluctuations, so that the approach mainly involves translational motion. For the purpose of localization, video cameras provide an effective and relatively inexpensive solution, working at a wide range of distances with an increasing accuracy and robustness during the approach. However, illumination conditions in space are especially challenging, due to the direct sunlight exposure and to the glossy surface of a satellite, that creates strong reflections and saturations and therefore a high level of background clutter and missing detections. We employ a monocular camera for mid-range tracking (20–5 m) and stereo camera at close-range (5–0.5 m), with the respective detection and tracking methods, both using intensity edges and robustly dealing with the above issues. Our tracking system has been extensively verified at the facility of the European Proximity Operations Simulator (EPOS) of DLR, which is a very realistic ground simulation able to reproduce sunlight conditions through a high power floodlight source, satellite surface properties using multilayer insulation foils, as well as orbital motion trajectories with ground-truth data, by means of two 6 DOF industrial robots. Results from this large dataset show the effectiveness and robustness of our method against the above difficulties.

1. Introduction

Ever since satellites have been placed on an orbit, the ability to access and service such precious space assets is a growing interest. The success in servicing with space shuttles, the Hubble telescope [1] and the International Space Station can be mentioned as pillars of on-orbit servicing (OOS) technology. In particular, spectacular success has been achieved in rendezvous and docking for the experimental mission Gemini [2], where Gemini 6 maneuvered to and kept in station with Gemini 7 within a 30 cm distance. Subsequent missions further validated rendezvous and docking, followed by a successful boosting of docked spacecrafts into higher orbits. Therefore, the onset of rendezvous and docking capability in 1960s can be considered a vital milestone of today's ambition for OOS.

Moreover, this task is now becoming essential as the number of ageing satellites has continued to increase and

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occupy precious orbits, such as the geostationary Earth orbit (GEO) which is a limited resource for communication satellites. OOS requires orbital manipulation of resident objects, including on one hand the capability to remove orbital debris in order to free and reuse the orbit, and on the other hand to repair, maintain and upgrade the client, thus extending its lifetime.

All servicing activities begin with an *approach* phase, where rendezvous and proximity operations are performed, and a *capture* phase, bringing the servicer and target satellite in contact. In this context, the client satellite can be cooperative or non-cooperative: cooperative satellites provide themselves features that make servicing activities easier, such as fiducial markers to help localization, or active guidance facilities to help rendezvous maneuvers. In this paper, we consider instead a partially cooperative[1] satellite, active but markerless, that is near end of its lifespan and still able to keep a controlled attitude due to its attitude and orbit control system (ACOS).

At any stage, the relative position and attitude between client and servicer must be determined. In the past rendezvous and docking missions for cooperative satellites, LIDAR based measurements have been intensively employed for estimating range and pose: for example, videometer for Automated Transfer Vehicle (ATV) [3], advanced video guidance sensor [4] for DART, and rendezvous and docking sensor for ATV Jules Verne. However, LIDAR has a relatively high weight and a rotating part which wears during time, and it consumes relatively much power. By contrast, cameras are passive and static devices, with a low weight and low power consumption. For example, the mass of rendezvous and docking sensor TriDAR [5], tested on board Space Shuttle Discovery during the STS-128 mission to the ISS, is about 28 kg. Similarly the JenaOptronik's rendezvous and docking sensor (RVS), LIDAR used in first European Automated Transfer Vehicle ATV “Jules Verne” weighs 14.5 kg and consumes a maximum power of 70 W, whereas the total mass and power consumption of our three cameras (a monocular mid-range and close-range stereo cameras) and target illumination system are about 9 kg and 28 W respectively. The two technologies operate differently in the harsh space environment: while the former can scan textureless surfaces and operate under relatively strong lighting, but it has a limited accuracy and cannot easily take advantage of local features (such as surface edges and texture), the latter can rely on accurate features, here mainly given by the object contours, as the surface is mostly textureless and glossy.

The space environment sees an intense, highly directional sunlight resulting in several bright and dark shadows, easily saturating the camera sensor. On the other hand, the Earth's albedo provides a source of diffuse light that can reduce image contrast. Additionally, the surface of a satellite is usually wrapped in multilayer insulation (MLI) material for thermal protection. Thus, the optical characteristics of the client and the sunlight environment give strong specular reflections, posing non-trivial difficulties to visual tracking. Furthermore, state of the art camera pose estimation methods are not robust for all object geometries and orientations (views), for example in case of symmetry or frontal planar surface where in-depth rotations are ill-conditioned. Therefore, instead of tracking the full 6D motion parameters, we exploit AOCS for alignment of the two satellites. On the other hand, sensor fusion is well known in compensating drawbacks of measurement errors from sensors, however attitude measurement from AOCS is sufficiently accurate and robust in our particular application.

1.1. Contribution and organization

This paper aims at a robust, camera-based tracking and motion estimation for approach and rendezvous of a space object under different sunlight conditions. Cameras are mounted on the servicer satellite, and used to determine the relative pose of the client in the presence of reflection, shadow, and saturation. In particular, we propose and implement practical and robust methods to localize and estimate the 3D position at close-range using a model of the satellite nozzle, which is a salient feature for most satellites, while using a model of the outer satellite contour for mid-range localization. From the experimental point of view, our contributions include the following: (1) We integrate and verify our method on an existing simulation hardware for vision-based navigation. The system includes two calibrated camera setups for close- and middle-range (respectively, stereo and monocular), a target illumination system (TIS) with two illumination units, and a ground operation system for in-flight configuration. (2) We generate several rendez-vous and docking trajectories, synchronised with the image acquisition module, for verification of our system using a ground simulator with two 6-DOF robots, providing accurate measurement of ground truth trajectories. (3) We study and analyze the effect on our vision system of image compression artifacts, sunlight intensity and direction. (4) We adapt and integrate state-of-the-art algorithms for model-based visual tracking, exploiting edge and region statistics, suitable for the above mentioned challenges of specular reflections, shadows and saturation.

The paper is organized as follows: in Section 1.2, we review related work to our vision-based localization method. Section 2 describes the localization methods for mid-range and close-range approach. Section 3 presents our experimental setup, while Section 4 discusses the related results with ground-truth comparison. Finally, Section 5 summarizes and concludes the paper.

1.2. Previous work

Despite the fact that active sensors such as LIDAR are effective for rendezvous, even under harsh lighting conditions (see for example the Neptec's Laser Camera System-LCS [6]), their high weight and power consumption prevent their intensive use for future missions, as passive, low weight and low power cameras are now widely available. Moreover, advances in image processing algorithms and computing power further motivate their usage for localization in space. However, as we have mentioned, specular reflections due to

[1] We call the satellite partially cooperative since its AOCS is available, but no visual markers mounted to aid vision-based rendezvous.