Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 61 (2018) 862–878

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Concurrent image-based visual servoing with adaptive zooming for non-cooperative rendezvous maneuvers

Jorge Pomares [a], Leonard Felicetti [b], Javier Pérez [a], M. Reza Emami [b,c,*]

[a] *University of Alicante, PO Box 99, 03080 Alicante, Spain*
[b] *Luleå University of Technology, Division of Space Technology, Box 848, Rymdcampus, 981 28 Kiruna, Sweden*
[c] *Space Mechatronics Group, University of Toronto, Institute for Aerospace Studies, Toronto M3H 5T6, Canada*

Received 30 April 2017; received in revised form 4 September 2017; accepted 31 October 2017
Available online 9 November 2017

Abstract

An image-based servo controller for the guidance of a spacecraft during non-cooperative rendezvous is presented in this paper. The controller directly utilizes the visual features from image frames of a target spacecraft for computing both attitude and orbital maneuvers concurrently. The utilization of adaptive optics, such as zooming cameras, is also addressed through developing an invariant-image servo controller. The controller allows for performing rendezvous maneuvers independently from the adjustments of the camera focal length, improving the performance and versatility of maneuvers. The stability of the proposed control scheme is proven analytically in the invariant space, and its viability is explored through numerical simulations.

Keywords: Non-cooperative rendezvous; Visual servoing; Zooming cameras; Spacecraft guidance navigation and control

1. Introduction

Space debris is becoming the issue of concern amongst the space community because of its repercussion on present and future space missions. Indeed, uncontrolled objects from the previous space missions are currently occupying important orbital slots, causing notable collision possibilities with operative and non-operative satellites (Schaub et al., 2015). Despite the recent adoption of some mitigation guidelines (IADC Space Debris Mitigation Guidelines, 2007) and the development of a network of space debris surveillance and awareness (Flohrer et al., 2008; Donath et al., 2010), the threat of such incidents cannot be totally averted. Collisions, as the one between Iridium 33 and Cosmos 2251 in 2009 (Wang, 2010), are still probable, and they can trigger cascade phenomena that may compromise future utilization of space, labelled as Kessler Syndrome (Kessler and Cour-Palais, 1978, Liou and Johnson, 2008, Liou, 2011). Therefore, the need for a solution to this problem has led the space community to investigating the viability of different debris removal strategies (Shan et al., 2016) and the definition and development of on-orbit servicing missions for satellite rescuing and repairing (Graham and Kingston, 2015). Specifically, the removal of large, uncontrolled objects seems to be a viable solution for eliminating potential sources of new debris that could overcrowd low-Earth orbits. Further, on-orbit service missions have been thought for extending the operational life of satellites that cannot be easily removed by de-orbiting maneuvers but has to be dismissed

---

* Corresponding author at: Luleå University of Technology, Division of Space Technology, Box 848, Rymdcampus, 981 28 Kiruna, Sweden.

E-mail addresses: jpomares@ua.es (J. Pomares), leonard.felicetti@ltu.se (L. Felicetti), jpalepuz@ua.es (J. Pérez), reza.emami@utoronto.ca, reza.emami@ltu.se (M.R. Emami).

https://doi.org/10.1016/j.asr.2017.10.054
0273-1177/

in graveyard orbits at their end-of-life, mostly in Geostationary Earth orbits.

Preliminary analyses and design concepts of both debris removal and on-orbit servicing missions have shown that a close encounter to the debris by chasing spacecraft is a more promising approach than distance manipulations and "touchless" technologies, such electrostatic tug, laser ablation, etc. (Shan et al., 2016). Regardless of the technology adopted for capturing the uncontrolled debris, e.g., robot manipulators, nets, harpoons etc., the rendezvous with an uncooperative objects can follow a well-defined scheme: the chaser spacecraft has to (a) reach the same orbit of the target debris; (b) perform phasing orbital maneuvers to reduce the distance from the target debris; (c) synchronize its attitude motion with respect to the target debris; and (d) perform the rendezvous maneuvers to allow for on-orbit servicing or debris grasping and removal operations (Felicetti et al., 2016).

An image-based approach is one of the most appealing choices for the uncooperative rendezvous, since this technique is considered a low cost, mainly passive and accurate (Palmerini et al., 2016). Furthermore, the technology readiness of space qualified cameras, as well as of the onboard computers, is mature enough that the techniques developed for the control of ground based robots can be easily implemented onboard (Alepuz et al., 2016). An example of automated rendezvous is the Automated Transfer Vehicle (ATV), where the relative position and attitude of the chasing vehicle with respect to the International Space Station (ISS) is reconstructed by identifying the visual features of a specific target attached to the ISS (Pinard et al., 2007; De Rosa and Curti, 2006). Another example is given by the PRISMA mission (Bodin et al., 2011), where two different camera systems have been used during the formation flying demonstration experiment: the Far Range Camera and the Close Range Camera. The far range camera has been used as a star-tracker, detecting the target spacecraft as a bright spot over a diffuse black background. Thus, only information concerning the line of sight could be used in the guidance, navigation and control loop for reducing the distance down to 20–30 m. The close range camera has been used instead for the proximity operations between the spacecraft, extracting more detailed visual features and reconstructing even the attitude of the target platform (Bodin et al., 2012).

The previously mentioned missions demonstrated the viability of vision based GNC loops for the rendezvous of cooperative targets and the actual challenge is represented by the extension of such techniques to non-cooperative targets, such as space debris or satellites to be recovered. The main difference between cooperative rendezvous and non-cooperative rendezvous is related to the target object that is generally not designed to perform a rendezvous. Therefore, the target does not send any information of its position to the chaser and it does not have specific "targets features" as well as specific docking system that can help the chaser spacecraft during the rendezvous and capture maneuvers. Further, the target satellite is generally tumbling, as the satellite is anymore able to control its attitude (Bonnal et al., 2013). Therefore, the navigation system of the chaser satellite should address all the issues related to the target acquisition and target motion identification by means of specific onboard sensors and real time image processing algorithms. Moreover, the chaser should be able to obtain information concerning its accurate relative positioning even if, in general, the range is undetermined during the far-distance, angles-only, navigation phases (Woffinden and Geller, 2009). Finally, the guidance system of the chaser should be designed in order to make possible the close approach to the target by taking into account the typology of the capture system as well as the characteristics and performance of the actuation system. In both Petit et al. (2011) and Gasbarri et al. (2014), experimental setups have been settled in order to test the vision-based tracking algorithms to a space-like scenario. The experimental results showed the robustness of the classical algorithms to relative chaser/target orientation motions under different illumination conditions. In Song et al. (2014), the feasibility of a monocular-based relative navigation system, for rendezvous and docking of a fully unknown space object, has been investigated and successfully verified by using two extended Kalman filters applied to the far and close approach phases, respectively. The utilization of LIDARs as main sensors for close approaches to uncooperative objects has been explored in Aghili et al. (2011), Woods and Christian (2016) and Opromolla et al. (2015). Further, a combined algorithm which uses vision-based predictions and motion planning for the actuation of robotic arms during the pre and post grasping phases is presented in Aghili (2012) and the application of visual servoing techniques to a dual arm robotic system is also investigated in Hafez et al. (2014). Stereoscopic vision techniques can be also applied for close rendezvous, as in Yu et al. (2014).

It is worth noting that the problem of vision based rendezvous has been always divided in far and close approach cases. This is essentially due to intrinsic characteristic of the used camera systems: optical system with fixed and predefined focal length have been implemented onboard in both ATV and PRISMA missions, as well as theoretical studies have been focused on the implementation of visual servoing techniques for close approaches to the target satellites. However, the use of adaptive optics, i.e. zooming cameras, could overcome these limitations and allow the development of an unified, robust and adaptive guidance and navigation strategy for the complete (far and close) rendezvous of uncooperative satellites. The current technology and the expected progresses on the development and integration of such kind of cameras onboard of space systems, allow the formulation and implementation of GNC schemes that use zooming cameras as main onboard sensing devices (Kolb et al., 2011; Hull et al., 1995; Rienow et al., 2016).

This paper proposes the use of a zooming camera to perform the guidance of a spacecraft with respect to an