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Direct image-based visual servoing of free-floating space manipulators

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ABSTRACT

This paper presents an image-based controller to perform the guidance of a free-floating robot manipulator. The manipulator has an eye-in-hand camera system, and is attached to a base satellite. The base is completely free and floating in space with no attitude control, and thus, freely reacting to the movements of the robot manipulator attached to it. The proposed image-based approach uses the system's kinematics and dynamics model, not only to achieve a desired location with respect to an observed object in space, but also to follow a desired trajectory with respect to the object. To do this, the paper presents an optimal control approach to guiding the free-floating satellite-mounted robot, using visual information and considering the optimization of the motor commands with respect to a specified metric along with chaos compensation. The proposed controller is applied to the visual control of a four-degree-of-freedom robot manipulator in different scenarios.

1. Introduction

The research and development of robot manipulators on satellites for space operations has had a remarkable growth within the past few years. These manipulators are especially suited for precise, complex, or even dangerous tasks for astronauts. Currently, the utilization of the robot manipulators mounted on satellites can be summarized into six categories [1]: i) assembly, maintenance and repair; ii) spacecraft deployment, release and retrieve; iii) extravehicular activity support; iv) inspection; v) refueling; and vi) multi-arm cooperation. Regarding the base spacecraft, two types of operations are considered and studied [2]: free-floating case, where the base is completely free and floating in space with no attitude control; and thus, freely reacting to the movements of the manipulator attached to it; and free-flying case, where the base is actively controlled, and thus, the system's attitude and position can be controlled. In this paper, the free-floating case is considered, where the robot manipulator must be positioned with respect to a tumbling object from which a set of visual features can be extracted by the eye-in-hand camera system. The classical approach to dealing with this kind of situations is divided into four phases [1]: i) observing and planning; ii) final approaching; iii) impact and capture; and iv) post-capturing stabilization; usually knowing all the parameters of the target object, but there are also some works that deal with the capturing and stabilization of objects with unknown dynamics [3]. The control strategy discussed in this paper will focus on observing and approaching the tumbling object. This paper presents a new image-based visual servoing approach, using the kinematics and dynamics model of this kind of robots, not only to achieve a desired location with respect to the observed object in the space, but also to follow a desired trajectory with respect to the tumbling object.

Classical visual servoing systems allow for carrying out point-to-point motion of a robot using visual information. A well-known classification of this kind of control systems divides them into position-based and image-based visual servoing [4]. In the first category, image features are extracted from the captured image and a model of the scene, and the target is used to determine its pose with respect to the frame attached to the camera. However, in the second category, pose estimation is omitted, and the control law is directly expressed in the image space. In this paper, visual information is used to perform the guidance of a free-floating satellite-mounted robot (FFSMR). In this case, an image-based approach allows for defining the control law directly in the image space, and does not need precise calibration and modeling (only a set of visual features must be extracted from the observed object as described through the paper). This approach is proposed in order to perform the guidance of the FFSMR with respect to space objects, such as orbital debris, small asteroids, or defunct spacecraft. Classical image-based visual servoing assumes that the

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robot is a perfect positioning device. This type of control does not take into account the system dynamics, which is not suitable when the robot executes fast and/or accurate movements. Few proposed image-based controllers take into account the non-linear dynamics model of robotic arms, usually referred to as direct visual servoing. By means of direct visual servoing, the internal control loop of servomotors is removed, so the visual servo control law directly provides the torque to be applied to the robot joints. Additionally, integrating the FFSMR dynamics in the visual controller allows for obtaining a relation between joint speeds and end-effector motion of the robot manipulator taking into account the base attitude disturbance during the tracking. As shown in the results section, the use of this approach during the tracking allows for increasing the tracking performance with respect to classical image-based visual servoing systems.

A great number of visual servoing approaches, proposed up to now to perform the guidance of in-orbit robot manipulators, use a position-based approach. In [5], a 3D model-based tracking is used for a space rendezvous mission. In this case, a vision-based navigation is proposed using a 21/2 D visual servoing approach [6], without considering the system dynamics. In [7], the same researchers present a generic tracking and pose estimation method suited for complex, textured or untextured objects in deep space environments, for space rendezvous and space debris removal purposes. Within this last topic we should mention the work presented in [8], where an estimation method of relative pose based on stereo vision is presented for the final phase of the rendezvous and docking of non-cooperative satellites. In [9], relative navigation method for rendezvous and docking of an unknown tumbling object using a monocular camera is presented. Two extended Kalman filters with different models are used for relative orbit estimation in far range and relative position and attitude estimation in close range. Within this topic, it is worth mentioning the works of Aghili (see e.g. [3,10]), which describe a combined prediction and motion planning approach for robotic arms during the phase of pre- and post-grasping of tumbling objects with unknown dynamics. A Kalman filter is employed to estimate the object dynamics used for the robot path planning. A position-based approach is used utilizing the system dynamics. In order to perform the in-orbit robot guidance without estimating the relative pose between the robot and the observed object, several researchers have proposed the use of image-based approaches. In [11], a classical image-based visual servoing applied to the Japanese Engineering Test Satellite VII (ETSVII) is proposed. As it is described in [12], multiple tasks can be controlled in a hierarchical manner. The last work presents a priority-based redundancy resolution at the velocity level. This method chooses one task as primary, and projects the other tasks (secondary, tertiary, etc.) into the null space of the primary task derivative. In [13], a classical image-based visual servoing approach is employed for the guidance of a mounted dual-arm space robot. The work is designed to complete the task of servoing the robot's end-effectors to the desired pose, while regulating the orientation of the base-satellite. The visual task is defined as a primary task, while regulating the attitude of the base satellite to zero is defined as a secondary task without considering the system dynamics. Image-based control is also used in the experimental test-bed proposed in [14]. The paper shows that it is possible to evaluate the elastic properties of a multibody manipulator, thanks to the analysis of the acquired images. In [15], a classical image-based, a position-based, and a switching approach are presented for autonomous satellite capture using an on-board manipulator with binocular hand-eye cameras without considering the system dynamics. In [16], the previous approach is simulated taking into account the system dynamics; however, a classical indirect implementation is considered. None of the previous implementations of image-based visual servoing systems for FFSMR considers a direct visual control approach. The need for integrating the system dynamics in the guidance of FFSMR using image information is discussed in works such as [15] and [17]. These works describe a set of ground verification systems, which can experimentally verify and test the reliability of visual servoing control systems and path planning of space robots. In [18], a direct image-based visual servoing approach for guiding a FFSMR using an eye-in-hand camera system is proposed. In this case, an inverse dynamics controller is developed to lock the projection of a feature point at a desired constant position on the image plane from an initial one. Contrary to previous papers, using the direct visual servoing approach proposed in this paper, the FFSMR is able to track a desired image trajectory with respect to an observed object (not only a positioning task). Additionally, this paper proposes an optimal control approach to guide the FFSMR using visual information. This approach allows for tracking trajectories considering the optimization of the motor commands with respect to a specified metric. As shown in the experimental results, the use of this controller, jointly with the integration of a chaos compensation technique, allows to increase the tracking precision and to reduce the base attitude disturbance during the tracking. The proposed controller is applied to the direct visual control of a FFSMR during the tracking of image trajectories.

The paper is divided into the following sections. First, the kinematics and dynamics of the FFSMR is defined. Next, the proposed optimal visual system is explained in Section 3. Section 4 discusses the simulation results, and Section 5 makes few concluding remarks.

2. Kinematics and dynamics of the FFSMR

2.1. System architecture and assumptions

Fig. 1 represents the main components of the FFSMR. With $q \in \Re^n$ are represented the generalized joint coordinates of the robot manipulator (in our case, $n = 4$). Frame $\{B\}$ is attached to the base satellite. The inertial coordinate frame is called $\{I\}$. The end-effector frame, $\{E\}$, is attached to the manipulator end-effector, and frame $\{C\}$ is the camera frame (attached to the camera). The camera extracts k visual feature points from the observed object $s = [\mathfrak{f}_{1x}, \mathfrak{f}_{1y}, \mathfrak{f}_{2x}, \mathfrak{f}_{2y}, \dots, \mathfrak{f}_{kx}, \mathfrak{f}_{ky}]^{\mathrm{T}} \in \Re^{2k}$. Therefore, the image-based direct visual controller must perform the FFSMR guidance to track the desired trajectory in the image space, $s_d(t)$.

As previously indicated, this paper defines a direct visual servoing system applied to a FFSMR for the tracking of image trajectories. Additionally, in this paper, we assume that:

a) The FFSMR will track an image trajectory defined with respect to a target object from which four visual features points can be extracted, i.e., $k = 4$. The presented controller can be easily extended to employ other kinds of visual primitive to perform the guidance (only the interaction matrix employed throughout the paper depends on the considered primitive [4]).
b) An eye-in-hand camera system is employed; therefore, a constant relation between the camera coordinate frame and the robot end-effector frame is considered.
c) The target undergoes constant linear and angular motion and its angular momentum is known in advance. An estimation can be obtained using previous works such as [19,20].
d) There are no external forces acting on the entire system. No gas-jet thrusters are used on the base satellite.
e) The capturing phase is not considered in this paper, therefore, there are no interaction forces between the FFSMR and the observed object.