Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 57 (2016) 1508–1514

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Incremental inverse kinematics based vision servo for autonomous robotic capture of non-cooperative space debris

Gangqi Dong, Z.H. Zhu *

Department of Earth and Space Science and Engineering, York University, 4700 Keele Street, Toronto, Ontario M3J 1P3, Canada

Received 31 October 2015; received in revised form 31 December 2015; accepted 12 January 2016
Available online 21 January 2016

Abstract

This paper proposed a new incremental inverse kinematics based vision servo approach for robotic manipulators to capture a non-cooperative target autonomously. The target's pose and motion are estimated by a vision system using integrated photogrammetry and EKF algorithm. Based on the estimated pose and motion of the target, the instantaneous desired position of the end-effector is predicted by inverse kinematics and the robotic manipulator is moved incrementally from its current configuration subject to the joint speed limits. This approach effectively eliminates the multiple solutions in the inverse kinematics and increases the robustness of the control algorithm. The proposed approach is validated by a hardware-in-the-loop simulation, where the pose and motion of the non-cooperative target is estimated by a real vision system. The simulation results demonstrate the effectiveness and robustness of the proposed estimation approach for the target and the incremental control strategy for the robotic manipulator.

Keywords: Visual servo; Autonomous capture; Non-cooperative target; Space debris; Active debris removal; Space robotic manipulator

1. Introduction

The increasing population of space debris in low and geo-stationary Earth orbits severely threats the safety of orbiting satellites and the long-term sustainability of space activities (Jankovic et al., 2015). To address the threat on a global base, the Inter-Agency Space Debris Coordination Committee (IADC) has suggested that certain remediation measures must be taken to stabilize the increasing trend of space debris population, for instance, by active debris removal (ADR) of a few large space debris per year from some crowded altitudes and inclinations of orbits (Liou, 2011). Numerous debris removal technologies have been proposed and investigated, such as the robotic debris removal (Jankovic et al., 2015), hybrid propulsion module (DeLuca et al., 2013), harpoon technology (Dudziak et al., 2015), and concepts considering end-of-mission self-deorbit by electrodynamic tethers (Zhong and Zhu, 2013), etc. Due to the similarity between the robotic on-orbit servicing (OOS) and ADR missions, the concept of autonomous ADR missions using space robotic manipulators is appealing in terms of technology readiness level. Although numerous human-in-the-loop OOS missions involving robotic captures of spacecraft were successfully performed (Yoshida, 2009), a fully autonomous robotic capture in space, especially considering non-cooperative objects is still an open subject facing enormous technical challenges (Flores-Abad et al., 2014). Recently, a preliminary concept design of guidance, navigation and control architecture to enable a safe and fuel-efficient capture of a non-cooperative target had been proposed (Jankovic et al., 2015), where the attention was focused on the close range autonomous rendezvous and proximity maneuver. In this paper, we focus

---

* Corresponding author. Tel.: +1 416 7362100x77729.
E-mail address: gzhu@yorku.ca (Z.H. Zhu).

http://dx.doi.org/10.1016/j.asr.2016.01.011

on the autonomous capture of a non-cooperative target by a robotic manipulator after the orbit maneuver being completed.

One of the most challenging tasks in the autonomous capture of a non-cooperative target is the identification of target's kinematic state. Considering the non-cooperative nature, the non-intrusive vision based filtering methods have been extensively adopted in the pose estimation of target (Aghili, 2012; Chen, 2012; Gasbarri et al., 2014; Janabi-Sharifi and Marey, 2010; Sabatini et al., 2013). Once the position and velocity of a target are obtained, an effective controller is required to control a robotic manipulator to capture the target autonomously. Ideally, the interception point between trajectories of the target and the end-effector in capture scenarios should be used as the desired position of the end-effector in control (Liu et al., 2015). However, due to the non-cooperative nature, the trajectory of target is unknown in advance and the determination of the interception point becomes a challenging task. The task is further complicated by the fact that the velocity of the end-effector is related to the configuration (joint angles) of robotic manipulator, which is time-variant and nonlinear. Thus, the interception point is also subject to the variation of interception time. In order to address this challenge, a kinematics based incremental control strategy for the robotic manipulator is proposed and examined in this work. Since the capture process of a space debris is relatively slow, it is more intuitive to regard the joint position (joint angles) as control input to gain higher control reliability instead of velocity or acceleration. The paper is organized as follows. Followed by this brief introduction, Section 2 is dedicated to the vision based kinematic state estimation of a non-cooperative target by an integrated photogrammetry and extended Kalman filter approach. A kinematics based incremental controller for the robotic manipulator is then presented in Section 3. Section 4 is dedicated to the validation by hardware-in-the-loop simulation and discussion. Finally, Section 5 concludes the paper.

2. Vision based kinematic identification of non-cooperative target

Consider a robotic manipulator system shown in Fig. 1. Assume a global frame is attached to the fixed part of the robotic manipulator, a camera frame is fixed to the center of image plane, and a target frame to the center of rotation of the target, respectively. The transformation between the global and the camera frame can be easily obtained according to the system configuration. The pose of a target can be described with respect to (w.r.t.) the camera frame, such as, $\{x_{To}, y_{To}, z_{To}, \theta_x, \theta_y, \theta_z\}^T$, where $\{x_{To}, y_{To}, z_{To}\}^T$ is the origin of the target frame in the camera frame and $\{\theta_x, \theta_y, \theta_z\}^T$ are the Euler angles of the target frame w.r.t. the camera frame.

Accordingly, an augmented homogeneous transformation between the target and the camera frame can be written as

$$\begin{Bmatrix} x_C \\ y_C \\ z_C \\ 1 \end{Bmatrix} = \left[\begin{array}{ccc|c} & & & x_{To} \\ & \mathbf{R}_{TC} & & y_{To} \\ & & & z_{To} \\ 0 & 0 & 0 & 1 \end{array}\right] \begin{Bmatrix} x_T \\ y_T \\ z_T \\ 1 \end{Bmatrix} \tag{1}$$

where $\mathbf{R}_{TC}$ denotes the rotational matrix from the target to the camera frame formed by the composition of trigonometric functions of Euler angles, $\{x_T, y_T, z_T\}^T$ denote the coordinates of a feature point on the target in the target frame and $\{x_C, y_C, z_C\}^T$ denote the corresponding coordinates of the same feature point in the camera frame.

Consider a pinhole camera with a focal length f. By assuming the y-axis of the camera frame pointing toward the target, the feature point is projected onto the image plane by

$$\begin{Bmatrix} x_m \\ z_m \end{Bmatrix} = -\frac{f}{y_C - f} \begin{Bmatrix} x_C \\ z_C \end{Bmatrix} \tag{2}$$

where $\{x_m, z_m\}^T$ denotes the measurable image coordinates.

Substituting Eq. (1) into (2) yields two independent equations for one feature point, which contains six unknowns: $\{x_{To}, y_{To}, z_{To}, \theta_x, \theta_y, \theta_z\}^T$. Theoretically, one needs at least three feature points to solve for the six unknowns. However, four feature points are widely adopted in literature to avoid the ambiguity and increase the robustness of algorithm (Dong and Zhu, 2015). Consequently, there will be eight equations with six unknowns, which can be solved by an iterative least square approach with an initial guess. The pose estimation of a non-cooperative target by the photogrammetry is a Markov process based on the current measurement, which is prone to the measurement noise. Moreover, the computational time of photogrammetry may vary widely due to the initial guess used in the algorithm at each time instant. As a result, the system sampling time interval may be affected, which is undesirable for real-time control. Another issue of the photogrammetry is that it does not solve for motion directly, which is an important control parameter in capturing the target by a robotic manipulator autonomously in a dynamic scenario. To address these challenges, an integrated photogrammetry and extended Kalman filter (EKF) is presented as follows.

Define the system variable vector as

$$\mathbf{X} = \{x_{To}, \dot{x}_{To}, y_{To}, \dot{y}_{To}, z_{To}, \dot{z}_{To}, \theta_x, \dot{\theta}_x, \theta_y, \dot{\theta}_y, \theta_z, \dot{\theta}_z\}^T$$

Assume the target motion can be approximated as a linear motion within each sampling time interval t_s if it is sufficiently small. Thus, the system model of the target can be expressed as

$$\mathbf{X}_k = \mathbf{A}\mathbf{X}_{k-1} + \mathbf{B}\boldsymbol{\omega}_{k-1} \tag{3}$$