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Position-based visual servo control of autonomous robotic manipulators

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This paper concerns the position-based visual servo control of autonomous robotic manipulators in space. It focuses on the development of a real-time vision-based pose and motion estimation algorithm of a non-cooperative target by photogrammetry and extended Kalman filter for robotic manipulators to perform autonomous capture. Optical flow algorithm is adopted to track the target features in order to improve the image processing efficiency. Then, a close-loop position-based visual servo control strategy is devised to determine the desired pose of the end-effector at the rendezvous point based on the estimated pose and motion of the target. The corresponding desired joint angles of the robotic manipulator in the joint space are derived by the inverse kinematics of the robotic manipulator. The developed algorithm and position-based visual servo control strategy are validated experimentally by a custom built robotic manipulator with an eye-in-hand configuration. The experimental results demonstrate the proposed estimation algorithm and control scheme are feasible and effective.

1. Introduction

Robotic manipulators have been widely used in space for docking, assembling, repairing and other on-orbit servicing operations [1–5]. For instance, Mobile Servicing System (MSS) or Canadarm2 [6], Japanese Experiment Module Remote Manipulator System (JEMRMS) [7] and European Robotic Arm (ERA) [8] are typical examples of robotic manipulators performing assembly, maintenance, and payloads exchanging tasks on International Space Station. These operations were conducted either autonomously or by human astronauts. Robotic manipulators mounted on Mars exploration rovers, such as, Viking 1 and 2 [9], Spirits and Opportunity [10], Phoenix [11] and Curiosity [12], were designed to collect soil samples and/or place instruments on a target. These tasks were performed by preprogrammed commands and controlled from the Earth directly or relayed by the Mars Orbiter. Cameras were used in these missions to monitor the movements of the manipulators and take photographs of the surroundings. Robotic manipulators of orbital docking systems, such as the Shuttle Remote Manipulator System [13] and Orbital Express [14], performed tasks of grappling, docking, refueling, repairing and/or servicing another spacecraft. Pure experimental systems, such as, ROTEX (Robot Technology Experiment) and ETS-VII (Engineering Test Satellite) [15] demonstrated the operations of assembling, grasping, docking and exchanging orbit replaceable units by robotic manipulators. Most of these missions employed human-in-the-loop control. Manual control from the Earth may result in long time delay, while sending astronauts into space to perform the tasks suffers higher cost and the possibility of life loss. To address these challenges, autonomous control is required and becomes a research highlight in the field of robotic technology [16,17].

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Nomenclature

$\boldsymbol{A}$	system transformation matrix
$\boldsymbol{B}$	process noise coefficient matrix
$\boldsymbol{E}$	residual error in the measurement
f	focal length of the camera
$\boldsymbol{H}$	Jacobian matrix of measurement model
$\boldsymbol{I}$	identity matrix
$\boldsymbol{J_c}$	Jacobian matrix of the pin-hole camera model
$\boldsymbol{J_r}$	Jacobian matrix of the robotic manipulator
$\boldsymbol{P}$	covariance matrix of system state variable
$\boldsymbol{Q}$	covariance matrix of process noise
$\boldsymbol{R}$	covariance matrix of measurement noise
t	sample time
$\boldsymbol{X}$	state variable
$\boldsymbol{Z}$	measurement vector
$(\cdot)^c$	control vector
$(\cdot)^d$	desired vector
$(\cdot)^t$	vector of the target
$(\bullet)_C$	coordinates in camera frame
$(\bullet)_m$	image coordinates
$(\bullet)_T$	coordinates in target frame
$(\bullet)_{To}$	coordinates of target frame origin in camera frame
d_6	variable of robotic gripper
$\boldsymbol{dX_p}$	correction term of the photogrammetry
$\boldsymbol{K_g}$	Kalman gain
$\boldsymbol{R_{TC}}$	rotational matrix from target frame to camera frame
$\boldsymbol{R_{CT}}$	rotational matrix from camera frame to target frame
$\boldsymbol{T_{cg}}$	transformation matrix from camera frame to global frame
$\boldsymbol{X_c}$	position of the grasp point in camera frame
$\boldsymbol{X_g}$	position of the grasp point in global frame
$\boldsymbol{X_p}$	photogrammetry estimated target pose in camera frame
$\boldsymbol{\delta}$	vector of image error
ε	pre-set tolerance of photogrammetry
$\boldsymbol{\mu}$	measurement noise vector
$\boldsymbol{\omega}$	process noise vector
$\boldsymbol{\Theta}$	main robotic joint angle vector
ΔT	estimated time for capture
$\theta_{1,2,3,4,5}$	angle of torso, shoulder, elbow, wrist roll and wrist yaw joints
$\theta_{x,y,z}$	target orientation refer to x, y, z axes of camera frame

Autonomous control of robotic manipulator to track and grasp a moving target requires the precise knowledge of the target's pose and motion. Because of the non-intrusive, non-damaging and non-contact nature, computer vision is favored exclusively as a sensing system to obtain the required information [2,16,18–22]. Accordingly, visual servo control system has been developed to control the pose of manipulator's end-effector with respect to the target based on the feedback of vision system. For instance, the position of a known moving object in the image plane can be tracked with a single mobile camera based on past images and past control inputs to the mobile platform [23]. The autonomous capture of a non-cooperative target by a robotic manipulator requires not only to track the motion of target [24,25] but also to predict the rendezvous point and follow a specific approaching trajectory by the end-effector based on the estimated pose and motion of the target [16,19].

The camera configuration in a visual servo robotic system can be either eye-in-hand or eye-to-hand [26]. The eye-in-hand camera is mounted on the end-effector to provide a close and precise view of the target while the eye-to-hand camera is installed beside the robot to monitor the whole workspace with a broad and relative less accurate scene of the target [27]. Based on the errors employed in control, the robotic visual servo may be categorized as: image-based, position-based, and hybrid visual servo [28,29]. The image-based visual servo (IBVS) controls robots by the error between the projected desired and actual positions in the 2D (two dimensional) image plane via an image Jacobian without reconstruction of the target. Thus, it is free from target model errors and less sensitive to camera calibration errors and measurement noise in images. Considerable efforts [30,31] have been devoted to track moving targets in 3D (three dimensional) space with eye-in-hand cameras using IBVS. Extended Kalman filter was introduced into the IBVS algorithm to address the navigation errors and actuation delays [32]. The perturbation to eye-in-hand cameras by the flexibility of robotic manipulator [33] was investigated to enhance the robustness of IBVS algorithm. However, the IBVS lacks 3D depth information of a target and additional measure is required to estimate the depth. The position-based visual servo (PBVS) controls the error between the desired and actual poses and motion of the end-effector directly in the 3D workspace. The advantage of the PBVS is that the pose of end-effector can be controlled relative to the target directly and naturally, while the drawbacks are that the pose and motion estimation is prone to camera calibration errors, target model accuracy, and image measurement noise. These challenges have been successfully addressed by many researchers to eliminate image errors caused by an uncalibrated camera [34,35] and suppress the image noise due to the vibration of camera resulting from flexible manipulators [36]. Finally, the hybrid visual servo, referred as 2½D visual servo in the literature, evaluates the control errors partially in the 3D workspace and partially on the 2D image plane. Although effective, the hybrid system is generally more complex than either IBVS or PBVS for implementation. In the current work, we adopted a single, calibrated and eye-in-hand camera with PBVS to simplify the system configuration and implementation in autonomous capture of non-cooperative targets.

The key issue in the autonomous capture of non-cooperative targets by PBVS robotic manipulator is the estimation of target's pose and motion with visual feedback