Acta Astronautica 136 (2017) 101–114

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Robust, fast and accurate vision-based localization of a cooperative target used for space robotic arm

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ARTICLE INFO

Keywords:
Space robotic arm
Visual measurement
Cooperative target
Edge detection
Marker localization
Pose measurement

ABSTRACT

When a space robotic arm deploys a payload, usually the pose between the cooperative target fixed on the payload and the hand-eye camera installed on the arm is calculated in real-time. A high-precision robust visual cooperative target localization method is proposed. Combing a circle, a line and dots as markers, a target that guarantees high detection rates is designed. Given an image, single-pixel-width smooth edges are drawn by a novel linking method. Circles are then quickly extracted using isophotes curvature. Around each circle, a square boundary in a pre-calculated proportion to the circle radius is set. In the boundary, the target is identified if certain numbers of lines exist. Based on the circle, the lines, and the target foreground and background intensities, markers are localized. Finally, the target pose is calculated by the Point-3-Perspective algorithm. The algorithm processes 8 frames per second with the target distance ranging from 0.3m to 1.5 m. It generated high-precision poses of above 97.5% on over 100,000 images regardless of camera background, target pose, illumination and motion blur. At 0.3 m, the rotation and translation errors were less than 0.015° and 0.2 mm. The proposed algorithm is very suitable for real-time visual measurement that requires high precision in aerospace.

1. Introduction

Space robotic arms [1,2] play an essential role in outer space. They help reassemble space station, move transfer vehicles, assist astronauts to walk in space, and dock with spacecrafts [3]. In order to capture target, usually, a camera is assembled on the robotic arm to measure the pose between the target and the arm [4–6]. As shown in Fig. 1, a hand-eye camera and an arresting device are installed on the robotic arm [7]; a cooperative target and a to-be-arrested device are fixed on the object. The hand-eye camera has to identify the cooperative target quickly from complex scenes, localize the fiducial markers on the target, calculate the relative pose between the target and the camera based on the marker coordinates, and then transfer the pose to the one between the arresting and to-be-arrested device so that the moving path of the arm can be planned.

It is challenging to guarantee a high identification rate of the cooperative target. The distance between the target and the camera ranges from 0.3m to 1.5 m, and is subject to pitch, yaw and roll. As the pose changes, the target appears very differently in the image. The complex mechanical structure of the to-be-arrested device also interferes with the target identification. To make the robotic arm move as quick as possible, the algorithm must run in (near) real-time. It should also be robust to a small degree of motion blur. Performing in space and open air, some other constraints must be taken into consideration. One is irregular lighting. Lighting intensity may be too weak, too strong, or uneven. The metal on the arm and the to-be-arrested device may generate glittering points in the image. Therefore the difficulty of identification and marker localization are largely increased, especially the latter. Another obstacle is the limited storage and speed of the chips that runs the algorithm. For outer space execution, chips must resist radiation and high-speed particles, have low power supply and endure large temperature range; therefore they usually have lower speed and smaller memory than civil products [8]. As a consequence, algorithms should be relatively simple and the target needs to be provided with visual clues making identification and orientation easier.

We designed a cooperative target using a circle, a line and dots as markers, as shown in Fig. 2. The design simplifies the detection and localization algorithm and guarantees high identification rates. A novel

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http://dx.doi.org/10.1016/j.actaastro.2017.03.008
Received 6 October 2016; Accepted 9 March 2017
Available online 12 March 2017
0094-5765/

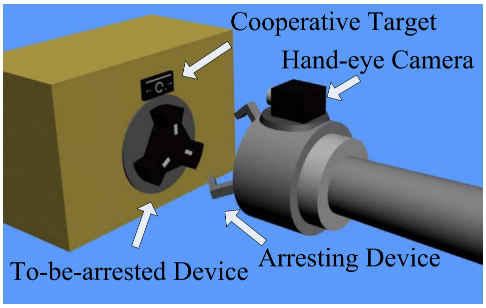

Fig. 1. Robotic arm with camera and grabber capturing an object with a target and connection structure.

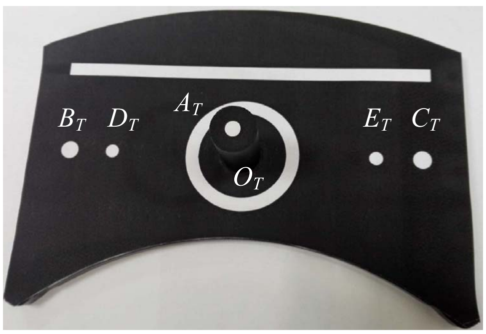

Fig. 2. Our cooperative target with distinct markers for optimal identification of location and orientation.

linking mechanism is proposed to obtain the interested single-pixel-width edges in a target image. Circles are detected from edges using isophote curvature. The target is identified if there exist one circle with certain number of straight lines in a boundary around the circle. The size of the boundary is related to a pre-computed ratio of the circle radius. In the target area, markers are localized using the target characteristics and a region growing algorithm. Based on the image coordinates of the markers, the target pose is measured with high precision at 8 frames per second. Our proposed algorithm is robust to lighting variance, complex scenes and small degree of motion blur, and very suitable for fast and accurate visual measurement with robotic arms.

2. Related work

Cooperative targets have been widely used in aerospace applications. In 1997, using a 2-point and a 3-point marker, the ETS-VII (Engineering Test Satellite VII) [9,10] developed by the JAXA (Japanese Space Agency) successfully demonstrated the RVD (Rendezvous and Docking) and RBT (space robotics) technologies. However, it is depending on a threshold commanded from the ground that the marker image is converted into a black and white image and then used to measure the pose. NASA (National Aeronautics and Space Administration) built the VGS (Video Guidance Sensor) in the mid 90 s and its improved version i.e. the AVGS (Advanced Video Guidance Sensor) in the early 21st centaury for automated spacecraft guidance. The VGS and AVGS use two wavelengths of lasers to illuminate a target that has a pattern of filtered retro-reflectors. One passes through the filters and generates a foreground image; the other is absorbed by the filters and produces the background image. Subtracting the former from the latter leaves an image with only the target's retro-reflectors visible. Then the target's pose is obtained by solving the perspective-N-point problem. However, the huge size and the requirement of two lasers as the illumination sources burden the hardware design and make the system costly. From 2012 to 2017, the Chinese Tiangong spaceships have performed a serious of autonomous dockings with the Shenzhou spacecrafts. In auto mode, a laser and rader system was used to measure the pose; in manual mode, a cross target was identified by the human eye. Our former work [11] proposes a visual method to identify a cooperative target with high accuracy rates. The target has one circle in the center and three lines adjacent with it, two long ones on the left and right, one short on the top. However, the circle's adjacent with lines increases the difficulty for both the circle and the line detection. This paper improves the former design by separating the circle and line, and increasing two abundant dot markers to guarantee pose measurement. Accordingly, we propose a new method that identifies the target with higher accuracy rates, and further explores the localization of the markers' centroids and high-precision target pose measurement.

A cooperative target could be identified using feature points or template matching. Well known point-feature descriptors like SIFT by [12] (scale invariant features transform) and SURF by [13] (speeded-up robust features) have robust identification and tracking capabilities. A method like Mutual Information – see e.g. [14] – is quite insensitive to changes in the lighting condition and to partial occlusions. However the huge computational load of these methods limits their hardware implementation in space.

For the identification of our target (see Fig. 2), edge extraction is an essential first step. The edges generated by the well-known Canny operator (see [15]) may be discontinuous or not single-pixel-width. To know the pixel coordinates of edges, another step i.e. edge tracking should be executed. Ref. [16] proposed a method that draws continuous and single-pixel-width edges in an image. It computes anchors first, and then link them to obtain edges. However, every time when the gradient direction of an edge point changes, say from vertical to horizontal, the linking algorithm has to try both the left and right walks to find edges, hence the complexity increases. To address this problem, we propose a novel linking method that makes the local optimum move at every step. It leads to smoother edges hence lays better foundation for further circle detection.

Circle detection is another key of target identification. Traditional methods like the circle Hough transform (CHT) by [17] are very slow and memory-demanding and produce many false detections. Improved method like randomized HT by [18] and local voting by [19] overcome some shortcomings but are either still slow or memory-demanding. Properties of isophotes (see [20,21]) makes them particularly suitable for object detection. Their shapes are independent of rotation and varying lighting conditions, hence isophotes curvature is used in this paper to detect circles.

Fiducial markers have been used for visual measurement by many researchers. Reference [22] arranged multiple dots in certain patterns as markers to measure the position and orientation of a spacecraft. Ref. [23] utilized a marker that consists of concentric contrasting circles to estimate the 12 Degrees of Freedom relative state for small inspection spacecrafts. Ref. [24] presented a coarse-to-fine dot array marker tracking method and implemented it in a vivo animal experiment. Ref. [25] implemented fiducial markers around a lung tumor for dynamic tumor tracking. However, these methods have not been tested in complex circumstances like uneven lighting or with motion blur.

The structure of this paper is as follows. Section 3 describes the cooperative target. The algorithm determining the relative pose is based on two steps:

1. Target Identification, presented in Section 4, consisting of the three steps 1) Single-pixel-width Edge Extraction, 2) Fast Circle Detection, and 3) Line Detection within a Boundary.
2. Marker Localization, explained in Section 5, using 1) Reference Values Extraction and 2) Accurate Marker Localization.Section 6 demonstrates exhaustive experiments. Conclusions are drawn in Section 7.