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On-orbit real-time robust cooperative target identification in complex background

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Abstract Cooperative target identification is the prerequisite for the relative position and orientation measurement between the space robot arm and the to-be-arrested object. We propose an on-orbit real-time robust algorithm for cooperative target identification in complex background using the features of circle and lines. It first extracts only the interested edges in the target image using an adaptive threshold and refines them to about single-pixel-width with improved non-maximum suppression. Adapting a novel tracking approach, edge segments changing smoothly in tangential directions are obtained. With a small amount of calculation, large numbers of invalid edges are removed. From the few remained edges, valid circular arcs are extracted and reassembled to obtain circles according to a reliable criterion. Finally, the target is identified if there are certain numbers of straight lines whose relative positions with the circle match the known target pattern. Experiments demonstrate that the proposed algorithm accurately identifies the cooperative target within the range of 0.3–1.5 m under complex background at the speed of 8 frames per second, regardless of lighting condition and target attitude. The proposed algorithm is very suitable for real-time visual measurement of space robot arm because of its robustness and small memory requirement.

1. Introduction

In space station, robot arms[1–4] are used to reach out from space shuttles to deploy, maneuver and capture payloads. For instance, they deploy and capture satellites, support spacewalking astronauts and help assemble the space station. All of these performances consist of three stages: object capturing, moving and releasing. During the capturing and releasing process, the

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space robot arm keeps calculating its relative position and orientation to the to-be-captured object and adjusting its moving path. As shown in Fig. 1, a cooperative target[5,6] and a to-be-arrested device are fixed on the object; a visual sensor (hand-eye camera) and an arresting device are placed on the space robot arm. The hand-eye camera takes images of the cooperative target, calculates their relative position and orientation using visual measurement methods and then transfers it to the POS (position and orientation) between the arresting and to-be-arrested device. According to the POS parameters, the moving path of the space robot arm is planned.

In order to precisely control the moving trajectory, the camera must calculate the POS between the arm and the object on orbit and in real-time. The initial step of POS calculation is identifying the cooperative target on the object. However, in order to guarantee the flexibility of the robot arm, the size and weight of the hand-eye camera are limited. Therefore, the chips inside the camera, including DSPs (Digital Signal Processors), FPGA (Field Programmable Gate Array) and MCU (Micro Controller), should also have limited size and weight. Performing in outer space, the chips in the camera must have low power supply, resist radiation and high-speed particles and endure large temperature range (lower than minus 100 to more than 120 °C). Chips meeting these requirements have lower speed and less memory storage than civil products.[7] Hence, the minimization of computational cost in target identification is a constant focus. Another obstacle is that the target background is complex. Various objects may appear in the background, including planet, star, spaceship and tool box. In day-light, the target is probably backlighted and the light intensity may be too weak, too strong or uneven. The metal on the space robot arm, satellite or spaceship is likely to generate glittering spots in the image.

Fig. 2 represents the cooperative target we use to calculate the relative POS parameters. It is painted by two flat paints, one black as the background and one white as the foreground. The pattern in the foreground consists of a ring, three lines and three dots. The ring and lines are designed for identification. Because circles rarely appear in outer space, the ring reduces the misidentification rate of the target. The dots are for POS measurement. Make point O the target center and column OA with dot A on its top is perpendicular to the target plane. Dots A, B and C consist of an isosceles triangle, with A as the vertex. Using the image coordinates of the centroids of the three dots, the POS between the space robot arm and the object is calculated by perspective-three-point (P3P) algorithm.

Using the characteristics of circle and lines, we propose an on-orbit real-time robust algorithm that identifies this cooperative target in complex background. The proposed algorithm

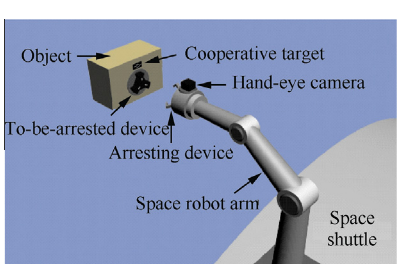

Fig. 1 Space robot arm capturing an object.

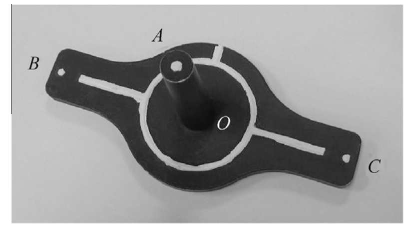

Fig. 2 Cooperative target.

first extracts the interested single-pixel-width edges using an adaptive threshold and improved non-maximum suppression. The memory amount is substantially decreased because a large number of irrelevant edges are ignored in this step. Then it follows a novel tracking algorithm to cluster pixels which change smoothly in tangential directions. According to a reliable criterion, the circles are retrieved with a small amount of computation and time. Then we set up two different sized square boundaries around each circle and detect straight lines in their complement areas. Finally, the cooperative target is identified if there are certain numbers of straight lines whose relative positions with the circle match the known target pattern. The proposed algorithm works in real-time and has a high accuracy rate. Regardless of lighting condition, distance and target attitude, it accurately identifies the target in complex background. Most importantly, it uses a very small amount of memory and can be easily deployed on DSPs. Therefore, it is very suitable for real-time robotic applications, such as POS measurement of space robot arm and robotic arms' manipulating objects on a production line.

2. Related work

During the middle 20th century to the early 21st century, various cooperative targets are used in space by different countries. Advance video guidance sensor (AVGS)[8,9] is the most widely used cooperative target on orbital vehicles by the United States of America. To identify it, two lasers of different wavelengths are used to illuminate the target. One passes through the filter in front of the retro-reflectors on the target and generates the foreground image; the other is absorbed by the filters and produces the background image. Then the foreground image subtracts the background image thresholds the result, leaving an image with only the target's retro-reflectors visible. AVGS determines the retro-reflectors' centroids and calculates the target's pose by solving the perspective-N-point problem. However, it is not suitable for visual measurement of space robot arm because of the huge size of AVGS. And its requirement of two lasers as the illumination sources increases the burden of hardware design of the hand-eye camera. When the Chinese Tiangong-1 performed docking with the Spaceships Shenzhou, 9 and 10, a cross target was used. In manual mode, it was identified by human eye; in automatic mode, it was identified using a laser and radar system. In only visual light, a cross target can be easily misidentified because lines appear constantly in outer space. And because the target is two-dimensional, it cannot be used to measure the six degrees of freedom (DOF) POS between an object and the space robot arm. Japanese Engineering Test Satellite-7(ETS-VII)[10] used a three-point non-coplanar marker