A Vision System for Autonomous Satellite Grapple with Attitude Thruster

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Abstract: This paper describes an experiment of a binocular vision-based system for positioning the thruster nozzle on the satellite mockup. Images of the thruster are obtained using two cameras in order to determine the thruster's 3D position. At the beginning the thruster is selected manually, and then a local image region is extracted from the raw image. Subsequently, a Canny detector algorithm is used in the local image region to acquire the edge roadmap, and a Hough Transform algorithm is performed to detect the features with circles. Then, a curving fitting method is employed to determine the position of the center of the thruster nozzle., The end effector keeps tracking the target thruster to the distance of 0.1 meter and grasps the target by prodicting its trajectory. The experiment has shown that the system is robust to camera/target relative motions and performs approaching and grappling procedures on satellite mockup successfully.

1 INTRODUCTION

The benefits of on-orbit satellite servicing include satellite refueling, satellite life extension, debris removal, repair and salvage. The robotic systems plays an important role in satellite servicing and satellite capture is a critical phase for enabling service operations. In the satellite operations the servicing vessel approaches the target satellite to a distance of about 2m. Then a robotic manipulator is used to autonomously capture the target satellite and perform the docking operation with the vehicle.

In last years several space missions have tested the satellite capture technology. In 2007 DARPA OrbitalExpress tested the rendezvous, approach, docking and servicing, including transfers of hydrazine fuel, and battery and flight computer orbital replacement units (Leinz 2008). The demonstration system consisted of two satellites, i.e. the ASTRO and the NextSat/CSC. ASTRO is the active (chaser) vehicle with the NextSat/CSC as the passive (target) vehicle. In this mission, the advanced video guidance sensor (AVGS) laser-based tracking system was employed to provide target attitude, range, and bearing during the chaser's short-range proximity maneuvering and docking operations that occurs in the last few hundred meters of flight down the approach corridor. The AVGS was designated to be an autonomous docking sensor using the reflectors which were equipped on the target. Also, the DARPA sponsored the FREND program to prove the capability of autonomously executing an unaided grapple of a spacecraft which was never designed to be serviced (Debus 2009). The FREND program was developed and demonstrated a flight robotic arm system with its associated avionics, end-effector, and algorithms. The EEVS (End Effector Vision System) was used to guide the arm into a hardpoint and position the figers for a solid grapple. The EEVS used three visible cameras mounted near the end of the robotic arm. In 2011 DARPA sponsored the Phoenix Plan program to develop the technologies to cooperatively harvest and reuse valuable components from retired, non-working satellites in GEO and demonstrate the ability to create new space systems at greatly reduced cost (David 2013). One of the most difficult problems to solve on the Phoenix Plan will be rendezvous and proximity operations through grappling of a retired satellite with properties that may be unknown. The Phoenix team undertook a test campaign to test a variety of LiDAR and optical sensors (e.g. stereo camera CCD sensor) for use during RPO maneuvers in the Phoenix mission.

Obviously, many satellites were not designed with servicing capabilities and do not have sensors

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or visual clues to assist with on-orbit capture. Therefore, a vision-based position estimation system must be able to use and track satellite natural geometric features to determine the relative position between the chaser and the target. Satellites have a number of well-known common features (such as thrusters, interface rings, solar panels, etc). Due to their location and structure properties, the thruster system has been proposed as a possible selection for satellite capture.

In this paper, a vision-based position estimation algorithm was developed. The system used a binocular stereo cameras CCD sensor and the thruster of a full scale satellite mockup to determine the position and grasp. The stereo camera system and the capture tool were mounted on the end effector of the robotic arm. The system was used at a standoff distance less than 1.2 meters to the target. To avoid the disturbance of similar thrusters, a method was proposed to reduce the scope of the stereo systerm output image by selecting the target thruster at the beginning. To accurately locate the center of the thruster, a Canny edge detection filter is executed on the stereo systerm output and a Hough Transform is designed to locate the circular contours of the thrusters. Therefore, the binocular positioning algorithm was used to calculate the position of the thruster in three dimensions in the end effector frame. At a standoff distance of 0.1 meters, the stereo system could not shot the images of the thruster as a whole because the thruster was sheltered by the capture tool. To accomplish the grappling of the thruster, a satellite motion estimation algorithm was proposed to predict the position of the thruster in the following seconds. This vision system was successfully employed to guide the end effector to capture the target thruster in the experiment of the robotic arm grappling.

2 VISION SYSTEM

2.1 Image Acquisition and Preprocessing

In order to have the entire thruster in the field of view, two cameras acquire gray images at a maximum resolution of 1024 by 1024 pixels and an image undistortion and calibration process is performed.

The vision system uses the thruster and its projection in the camera image to set the position problem. The position is defined as the center of the thruster nozzle. The layout of the satellite mockup is designed including two thrusters and other accessories.

Because the thruster A is the same as the thruster B, the thruster to be captured (e.g. thruster A) should be selected manually at the beginning. When the vision system is working, the image of the thruster B disturbs the recognition of the thruster A. So, the local area around the thruster A is selected. The local area is a square with sides of length 4 times of diameter of the thruster A's circle, as shown in figure 1.

2.2 Image Edge Extraction

The gray images are then processed by a Canny edge detector to find the edge binary map (Canny 1986). The algorithm of the Canny edge detector can be described as follows.

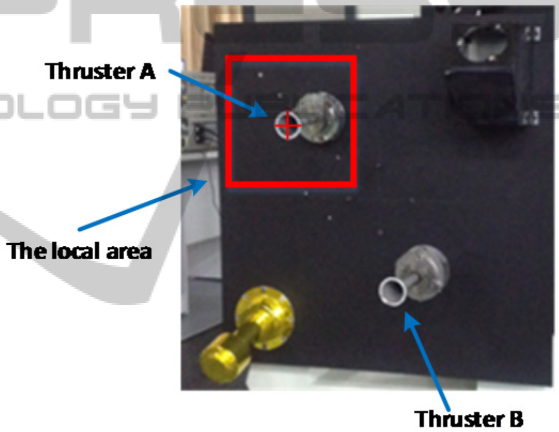

Figure 1: The local area around the radius of the thruster A.

Firstly, because the Canny edge detector is susceptible to noise in raw unprocessed image data, it uses a filter based on a Gaussian curve, where the raw image is convolved with a Gaussian filter. The result is a slightly blurred version of the original which is not affected by a single noisy pixel to any significant degree.

Secondly, the edge detection operator returns a value for the first derivative in the horizontal direction (Gx) and the vertical direction (Gy). From this the edge gradient and direction can be determined:

$$G = \sqrt{G_x^2 + G_y^2}$$

$$\theta = a\tan(\frac{G_y}{G_x})$$

Where G is the edge gradient and θ is the direction angle from the arctangent function with two arguments. The edge direction angle is rounded to one of four angles representing vertical, horizontal and the two diagonals (i.e. 0, 45, 90 and 135 degrees).

Thirdly, given estimates of the image gradients, a search is carried out to determine if the gradient magnitude assumes a local maximum in the gradient direction. Edges give rise to ridges in the gradient magnitude image. The algorithm then tracks along the top of these ridges and sets to zero all pixels that are not actually on the ridge top so as to give a thin line in the output. The tracking process exhibits hysteresis controlled by two thresholds: T1 and T2, where T1 = 100 and T2 = 200. Then the edge binary map can be obtained.

2.3 Image Circle Feature Recognition

The input of this subsystem is the edge binary map of the image acquired by the cameras. Next, the circles on the image are extracted using the Hough Transform algorithm. The Hough Transform is a means of cateloging the components of the edge image. A contour extraction algorithm is used to extract the circles and locate a circle with a maximum diameter in the image representing a thruster nozzle.

2.4 Curve Fitting

From the section 2.3, we have detected a circle in images of the left and right camera respectively, that is circle L and circle R. The detected circle L and circle R are not “real circles”, are ellipses in fact. Thus, we use an ellipse fitting algorithm to fit the circles acquired by two cameras (Chen 2007). Then, we calculate the coordinates of the origins of the two ellipses with respect to the image frame.

2.5 Position Calculation

The input of the position calculation system is the coordinates of projected pixel points of the origins of the ellipses. The two pixel points with respect to the image frame are corresponding to the center of the ellipse with respect to the camera frame. Thus, the geometry of the two cameras and the method are used to calculate the center of the ellipse with respect to the camera frame (Zhang 1999).

2.6 Target Motion Estimation

When the robot arm approaches the thruster at a standoff distance of 0.1 meters, the stereo system could not shot the images of the thruster as a whole because the thruster was sheltered by the capture tool, as shown in figure 2.

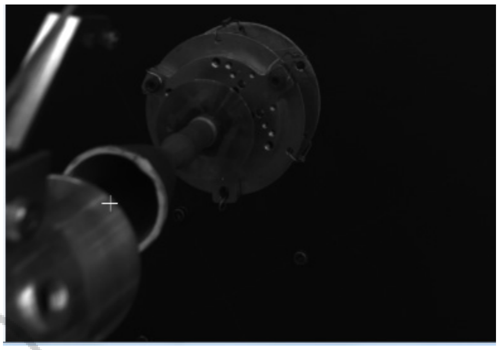

Figure 2: The thruster is sheltered by the capture tool.

The target satellite motion is a single-axis rotation around normal vector of the satellite plane. Thus we move the robot arm to track the rotating thruster at a standoff distance of 0.1 meters for 20 seconds to predict the trajectory of the thruster. Furthermore, due to the predicted trajectory, we can calculate the position of the thruster and accomplish the thruster grappling.

3 EXPERIMENTAL SETUP

The experimental setup, shown in figure 3, consists of a chaser robotic manipulator along with an end-effector containing the binocular cameras and the capture tool. The satellite mockup simulates the plane of satellites and consists of a 1.5m by 1.5m base covered with two thrusters and other accessories. A single-degree turn table moves the mockup to rotate around the axis of the turn table.

The camera used in this experiment is a Pantera 1M30, with a resolution of 1024 by 1024 pixels and a maximum frame rate of 30 fps. The cameras are located at an appropriate angle of 15 degrees with respect to the capture-tool longitude axis such that the entire thruster can be viewed by the cameras, as shown as figure 4.

The algorithm is implemented in Visual C++ and runs on a desktop with windows XP operating system equipped with an Intel Core 2Duo processor. A data logging system saves the images shot by the binocular cameras.

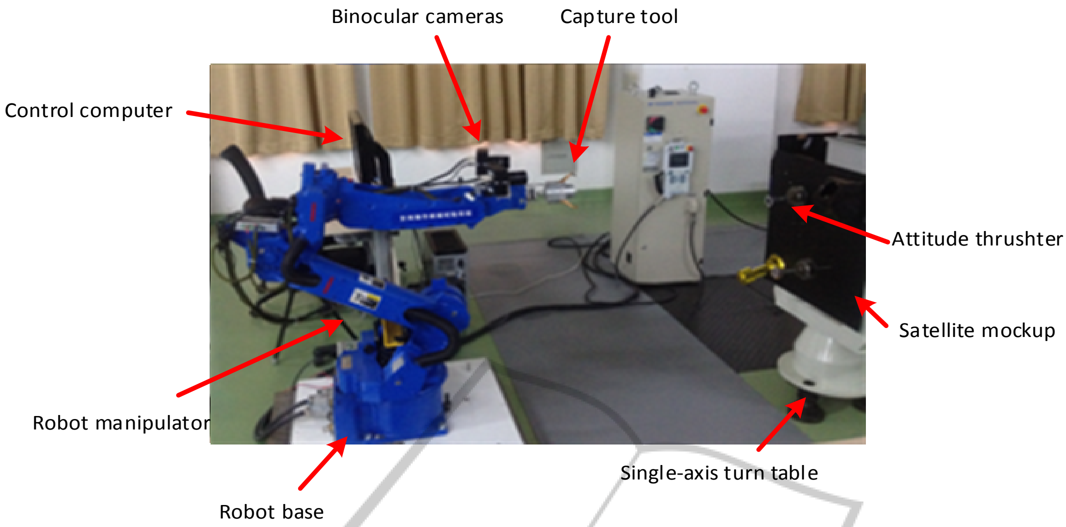

Figure 3: The experimental setup.

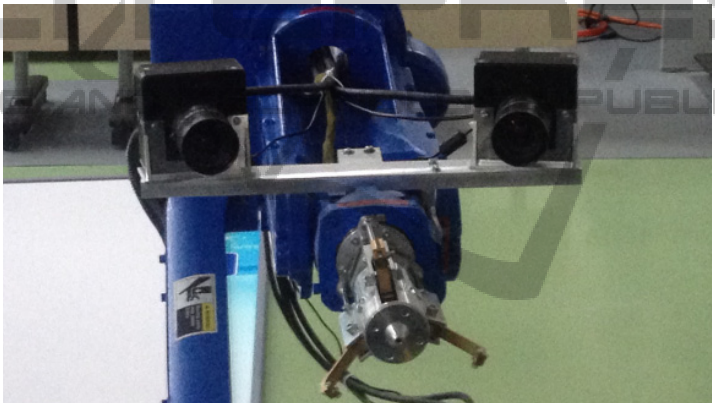

Figure 4: The binocular cameras and the capture tool.

4 EXPERIMENTAL RESULTS

4.1 Testing Procedure

In the experiment, one of the two thrusters, of radius R, was selected manually at the beginning and a local image square area centred at the selected thruster is acquired. The robot manipulator keeps tracking and approaching the selected thruster to a standoff distance of 0.1 meters. Then, the robot manipulator keeps this distance of 0.1 meters to the thruster to predict the trajectory of the thruste. Due to the predicted trajectory, the end effector continues to approach the thruster until capturing the thruster.

4.2 Experimental Results

The images shot by the left and right camera are shown as figure 5. The cross denotes the center of the recognized thruster. In the course of the manipulator approaching, the vision system can recognize the selected thruster and determine its position at all times. The vision system played an important role in the grappling control system. The grappling of the thruster is shown as figure 6.

5 CONCLUSIONS

The binocular vision system are adequate to perform approaching and grappling procedures on satellite mockup with attitude thruster as studied in this work. After selecting the thruster manually, the vision system can track the target thruster and determine the position of the thruster continuously. A future development is the implementation of a system that reconstructs the shape of the target

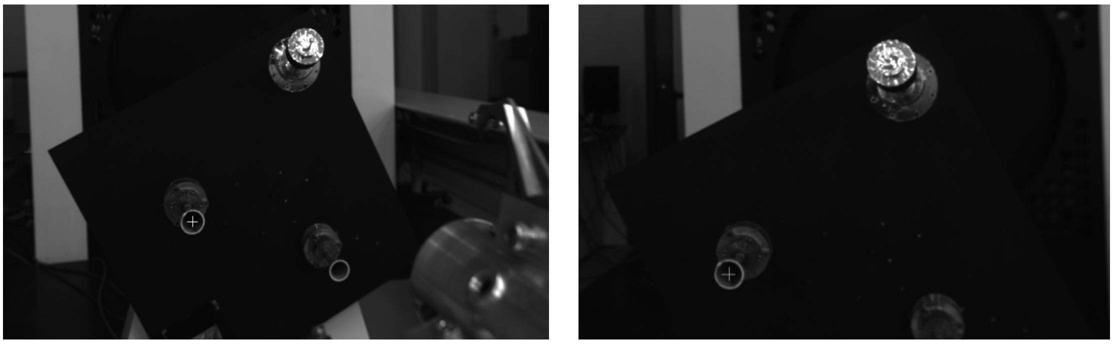

Figure 5: The images shot by left and right cameras at a distance of 1 meter.

(The cross denotes the center of the recognized thruster)

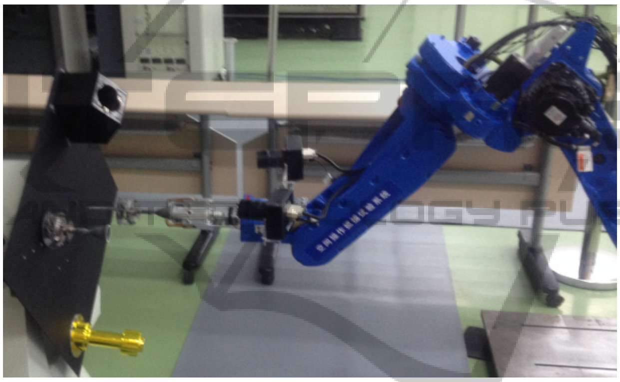

Figure 6: The thruster is grappled by the capture tool with the help of the vision system.

satellite and recognizes the common features (e.g. interface rings, thrusters, solar panels and etc.) from this shape.

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