Position Measurements of the Space Manipulator based on Monocular Microscope Vision

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Abstract. In this paper, an inspection manipulator with a micro-camera at the end was designed for in-situ microscopic observation of samples on the material exposure platform. In order to achieve the positioning requirements, a novel position measurement method for the manipulator was proposed based on monocular microscope vision. First, a planar target was designed for feature detection. Next, the measurement task was performed in two steps respectively. On the image plane, a motion-based active calibration method was used to measure the translation. For the rotation around Z axis, the relationship between the image blur \( b \) and the rotation \( \theta \) was fitted to estimate the rotation from images. In final, the proposed approach was tested in term of accuracy and robustness in ground experimental conditions. The focusing error of the piezoelectric motor was about 1\( \mu \)m and the obtained average alignment accuracies were less than 10\( \mu \)m in X, Y, and 0.002° around Z, respectively, which satisfied the positioning requirements of the in-situ observation.

1. Introduction

The China Space Station is an important experiment base for China's space science and new technology research. Considering the threats of space environment to the reliability and safety of all robotic space exploration missions [1], advance in the space environmental effects on materials and devices has been considered as a crucial program for China Space Station Construction. The material exposure device, which is mounted outside the China Space Station, is an observation platform developed for the study of the space environment. And an inspection manipulator is designed to drive the microscope camera to observe the samples on the exposed surface in-situ. In this case, success in meeting the observation requirements will rely on the positioning accuracy of the manipulator.

Generally, the position measurement methods in the space environment can be simply classified into three categories [2-5]: (1) Multiple sensor fusion approach integrates information from multiple sources, especially active sensing technology, such as 2D-PSD (Position Sensitive Detector), Laser Rangefinder, and Structured lighting, etc. It is widely used in the occasion with a large detection range, even though the hardware cost is generally high. ESA (European Space Agency) designed a geostationary orbit restorer to capture abandoned satellites in orbit, where the laser ranging and active vision measures were used [6]; (2) Stereo vision belongs to a passive measurement method. The principle is recovering the 3D information of the object from multiple images. In space environment, it commonly occurs in spacecraft surface inspection and close manipulator on-orbit, but the time consuming correspondence problems still exist. Jasiobedski et al. [7] proposed a stereo–
vision-camera-based vision system to measure pose and track satellites; (3) Monocular vision is the most simple measurement method, which is frequently integrated into the small robot system. It has the advantages of simple structure and flexible operation. The Space Station Remote Manipulator System (SSRMS or Canadarm2) [8], European Robotic Arm (ERA) [9], Japanese Experiment Module Remote Manipulator System (JEMRMS) [10] and most other space manipulators have monocular camera mounted on the manipulator end-effector. While, the accuracy of monocular vision is mainly limited by the measurement error along the optical axis [11].

Micro-vision is a new technology for precision measurement that combines computer vision and microscopic imaging. And its geometric scale of the object can range from millimeter to micrometer, so that it has been widely used in robot micro-operation [12]. In order to realize the position measurement with the least hardware resources, a novel position precision measurement method based on the monocular microscope vision system is proposed, which provides maximum utility and flexibility for the observation experiments.

2. Inspection manipulator system
On the material exposure device, the modular experiment containers for mounting and exposing samples is plugged on the four sides of a base plate. To have a global observation of the base, the inspection manipulator is designed as a 4-DOF cylindrical manipulator. As figure 1 shows, the $J_1, J_2, J_3$ of manipulator correspond to the $r, \theta, z$ in cylindrical coordinate and the $J_3$ is the degree of freedom of rotation around Z axis. More details about the main components and the specific parameters of the manipulator can be seen in table 1.

![Main components of Space Inspection Manipulator system](image)

**Figure 1.** Main components of Space Inspection Manipulator system

|        | $J_1$ | $J_2$ | $J_3$ | $J_4$ |
|--------|-------|-------|-------|-------|
| Type   | revolute | prismatic | revolute | prismatic |
| Mass   | 1.93kg | 3.06kg | 5.58kg | |
| Range  | 0–360° | <223mm | 0–360° | <385mm |
| Reduction ratio | 1/100 | 2mm/rev | 1/100 | 2mm/rev |

3. Position measurement method
Comparing to conventional vision, microscope vision systems usually have some special imaging characteristics, including small view depth, small view field, and neglectable lens distortion, which are mainly determined by the magnification factor of lens. As discussed in [13], the view depth is neglectable comparing to the object distance, thus, the object distance can be considered as a constant. Obviously, in the condition that the image is clear, the sensitive freedoms of the microscope vision
system are two translation motions on the image plane and one rotation motion around Z axis, respectively. Therefore, the measurement work is performed in the corresponding two steps.

3.1 Design of target
Selecting an appropriate target can not only simplify the difficulty of feature extraction, but also improve the accuracy of visual calibration[14]. In this paper, a planar target is designed as shown in the figure 2, which includes a “cross” in the center and a series of triangles pointing to the center. The size of target is 1mm×1mm and the distribution of targets A, B, C, D on an exposure surface is shown in figure 3.

![Figure 2. Planar target design](image1)

![Figure 3. Distribution of targets on an exposure surface](image2)

Limited by the small view field of microscope vision system, it is likely that only a few target’s features are captured, which will affect the precision of position measurement. Thus, the manipulator is driven to move approach “cross” based on the features in images. The main steps are as follows: (1) Detect all closed triangle in the feature detection area (450pixels×450pixels) and get their centroid coordinates; (2) Select the triangle nearest to the center of image; (3) Move in a fixed step of 0.1mm in the direction of the altitude vector of the triangle; and Repeat (1)~(3) until the “cross” appears in the view.

3.2 Translation on the Image Plane
The measurement of the translation motion on the image plane need to be done continuously and quickly, so the traditional pattern-based calibration method is not suitable. Instead, a motion-based active calibration method is used. Since the image plane is parallel to the exposure surface, the measurements satisfy the plane constraint. Assume that $\begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix}$ is the relative position vector in Cartesian space, $\begin{bmatrix} \Delta u \\ \Delta v \end{bmatrix}$ is relative pixel vector in image space, the relationship can be expressed as follows.

$$
\begin{bmatrix}
\Delta x \\
\Delta y
\end{bmatrix} =
\begin{bmatrix}
J_{11} & J_{12} \\
J_{21} & J_{22}
\end{bmatrix}
\begin{bmatrix}
\Delta u \\
\Delta v
\end{bmatrix}
$$

(1)

where, $J_{i}$ $(i = 1, 2)$ is the element of the image Jacobean matrix.

The image Jacobean matrix can be solved by form an equation group:

$$
\begin{bmatrix}
\Delta x_1 & \Delta x_2 & \cdots & \Delta x_n \\
\Delta y_1 & \Delta y_2 & \cdots & \Delta y_n
\end{bmatrix} =
\begin{bmatrix}
J_{11} & J_{12} \\
J_{21} & J_{22}
\end{bmatrix}
\begin{bmatrix}
\Delta u_1 \\
\Delta v_1 \\
\Delta u_2 \\
\Delta v_2 \\
\cdots \\
\Delta u_n \\
\Delta v_n
\end{bmatrix}
$$

(2)

The least square solution of (2) is:

$$
J = AB^T (BB^T)^{-1}
$$

(3)
where,  \( A = \begin{bmatrix} \Delta x_1 & \Delta x_2 & \cdots & \Delta x_n \\ \Delta y_1 & \Delta y_2 & \cdots & \Delta y_n \end{bmatrix} \),  \( B = \begin{bmatrix} \Delta u_1 & \Delta u_2 & \cdots & \Delta u_n \\ \Delta v_1 & \Delta v_2 & \cdots & \Delta v_n \end{bmatrix} \)

### 3.3 Rotation around the Z Axis

Based on the optical imaging model shown in Figure 4, when \( f \) (focal length), \( u \) (distance of object from the principal) and \( v \) (distance of the focused image from lens) satisfy (4), the image is focused. And defocus will occur when object is outside the focal plane. Specially for the microscope vision system, a slight displacement along the optical axis direction may cause image blur, which is an important cue of rotation estimation from microscopic image.

\[
\frac{1}{u} + \frac{1}{v} = \frac{1}{f}
\]

(4)

![Figure 4. Optical imaging model of camera](image)

In order to find the relationship between the image blur \( b \) and the rotation \( \theta \), the CPBD (Cumulative Probability of Blur Detection) proposed by Marziliano et al, is adopted for blur detection in this paper. The principle is utilizing the edge width together with the concept of just noticeable blur (JNB) to obtain the fuzzy probability [15], and it has advantages including: near real-time, low computational complexity and good performance independent of the image content [16].

### 4 Experiment and Result

#### 4.1 Experiment System

Experiments are conducted with the inspection manipulator system, which consists of an air-bearing table, an operation platform, a manipulator and a microscope vision system, as shown in figure 5. The microscope lens is OLYMPUS LMPLFLN20x (WD=12mm, Mob=20, FOV=0.6mm×0.8mm) and the camera is selected to RZIMAGE RZUH-500C CCD module(PPI=2592X1944, PX=2.2μm×2.2μm).

![Figure 5. Experiment system configuration](image)
4.2 Results and analysis
The measurement process includes two stages, which are both automatically controlled. The first one can be taken as the initialization of the work, where the manipulator is controlled with motion commands. When the target is captured, a piezoelectric motor is used to drive the micro-camera to achieve auto-focus based on the climbing hill algorithm, whose positioning accuracy is about 1μm. During the later experiment, the object distance is not changed.

And to capture more features of the target, the manipulator is moved approach the center of image with the method of image recognition process in section 3.1, as shown in figure 6.

Figure 6. Image recognition process in the initialization of the measurement

The second stage is the main work of the measurement, which is completed in two steps: translation measurement on the image plane and rotation measurement around Z axis.

On the image plane, the microscope vision system is first calibrated with the method in section 3.2. When the camera is adjusted to the surface of the clear view, 4 groups of data are recorded in different positions on a plane, as listed in A and B in (5) and (6). Thus, the Jacobean matrix J is computed as given in (7). After the calibration, the manipulator is moved to a lot of points, where the relative positions measured in experiment are compared with the calculated value. And the statistical results can be seen in table 2. The maximum measuring error is less than 10μm in any direction. Figure 7 shows 10 sets of them.

\[
A = \begin{bmatrix}
0.3257 & 0.2098 & -0.3810 & 0.0463 \\
-0.2322 & 0.2145 & -0.1219 & -0.2964
\end{bmatrix} mm
\] (5)

\[
B = \begin{bmatrix}
843 & 587 & -1030 & 88 \\
-705 & 653 & -372 & -894
\end{bmatrix} pixel
\] (6)

\[
J = \begin{bmatrix}
0.3746 & -0.0147 \\
-0.0005 & 0.3300
\end{bmatrix}
\] (7)

The second step is the rotation \( \theta \) measurement around Z axis, and the method is to fit the relationship between the image blur \( b \) and the rotation \( \theta \). First, a target \( A \) is selected, where only joint 3 is driven both clockwise and counterclockwise to capture the corresponding blur images and other joints stay still. The range is from -0.04° to 0.04° with a scanning step of 0.005°. Then, the image blur \( b \) is calculated based on the CPBD algorithm. And the same operation is carried out at other two targets \( B,C \). From the curve shown in figure 8, the relationship between the image blur \( b \) and the rotation \( \theta \) is approximate to a quadratic curve, therefore, the fitting function is obtained as in (8). Furthermore, the error analysis is made and it is shown in table 2.

\[
b = 701.1\theta^2 + 3.765\theta + 0.0176
\] (8)
Figure 7. Comparison between the measured position and the calculated position

Figure 8. The curve of the image blur \( b \) with the rotation \( \theta \)

Table 2. Error analysis results.

|                          | AVE     | MSE    |
|--------------------------|---------|--------|
| Translation in X,Y axis /mm | 0.0089  | 0.0154 |
| Rotation around the Z axis /° | 0.002   | 0.001  |

5 Conclusion

In this paper, a novel position measurement method of space manipulator based on the monocular microscopic vision and artificial planar target was studied. And a measurement strategy including two stages was proposed. In the first stage, the micro-camera was driven to focus and the manipulator was controlled to approach the target. In the second stage, the measurements were performed in two steps: 1) the translation on the image plane was measured with the motion-based active calibration method; 2) the rotation around Z axis was obtained by fitting the relationship between the image blur \( b \) and the rotation \( \theta \). Within the allowable range of error, the ground experiment results showed that the focusing error of the piezoelectric motor along the optical axis was about 1μm, and the average position measurement error in X,Y axis and around the Z axis were less than 10μm, 0.002°, respectively, which satisfied the positioning requirements of the in-situ observation for the exposure platform.

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