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Pose Measurement for Capture of Large Satellite Docking Ring Based on Double-Line Structured Light Vision

Jun Yang[1,2,a], Xuehai Gao[1,3,b,*], Zhiheng Li[1,c], Shunzhi Li[1,2,d] and Bin Liang[1,e]

[1]Graduate School at Shenzhen, Tsinghua University, Xili, Shenzhen, China
[2]Shenzhen Laboratory of Space Robotics & Telescience, Xili, Shenzhen, China
[3]Shenzhen Engineering Laboratory of Geometry Measurement Technology, Xili, Shenzhen, China

[a]yangjun603, [b]gaoxuehai, [c]li.zhiheng@sz.tsinghua.edu.cn, [d]lisz15@mail.tsinghua.edu.cn, [e]bliang@tsinghua.edu.cn
*corresponding author

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Abstract: For on-orbit servicing of large valuable satellite, docking ring is a typical and strong component, which is fit for grasping by a space robot manipulator. In this paper, a novel method for measuring the relative pose of partial docking ring is proposed by introducing double-line structured light. Firstly, the double-line structured light vision measurement model is established. The model need only partial docking ring to compute pose. Secondly, the pose determination algorithm is presented. Using the four intersection points between the double-line structured light and partial docking ring, the position and attitude of the docking ring can be uniquely determined. Finally, the mathematical simulation model is built and the measurement error factors are analyzed. The simulation results show that the measurement method is effective and feasible.

1. Introduction

In the future, a space robot equipped with tools will be used to extend large valuable satellites' lifespans - even if they were not designed to be serviced on orbit. For on-orbit servicing of repairing, refuelling and relocating, a space robot manipulator has to grasp these satellites called non-cooperative targets. In the grasping process, the space robot manipulator needs to measure the relative pose of non-cooperative targets in real-time.

Some scholars research on non-cooperative pose measurement methods based on feature points by using geometric features such as solar panels and communication antennas [1]-[4]. However, these components are not strong enough to be grasped by a space robot manipulator. Most satellites have docking ring component which is used for mechanical connection with rocket in launching process. The docking ring component can provide circular feature constraint for pose measurement, and has strong stiffness for grasping. The Restore-L Robotic Servicing Mission of SSPD (Satellite Servicing Projects Division of NASA) will plan to grasp, refuel and relocate a government-owned satellite to extend its life in 2020 [5]. An artist's concept of measuring and grasping the docking ring by Restore-L servicer is shown in Figure 1. Therefore, the method of relative pose measurement by using docking ring is of considerable practical value. Miao and Zhu et al. [6] proposed a method for

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eliminating the false solution using Euclidean invariance of a known point to the centre distance as constraint, and then solving relative position and attitude of the circular feature. Meng and Xue et al. [7] presented a new method for monocular position-pose measurement, which is based on the circular and linear features. The linear feature is used to obtain the roll angle and eliminate the ambiguity. Liu and Zhao et al. [8] presented an approach for measurement of pitch, roll and yaw angles based on a circular feature. The approach depends on diameter features to compute rotational angles. Liu and Xie et al. [9] proposed a circular feature measurement method based on binocular stereo vision. The method can get the unique solution without using a correspondence criterion. Li and Liang et al. [10] provided a pose measurement method of non-cooperative circular feature based on line structured light. Using the two intersection points of line structured light and circular feature, the method eliminates the ambiguity and calculates the pose of the circular plane. The above-mentioned methods all need the whole circular feature. However, in practice, the docking ring's diameter of a large valuable satellite is more than one meter. A camera measurement system usually is mounted on the end-effector of manipulator. Limited by field of view, the camera can only obtain partial circular feature of the docking ring in close distance. Therefore, the above-mentioned methods have limitations during the grasping process of manipulator.

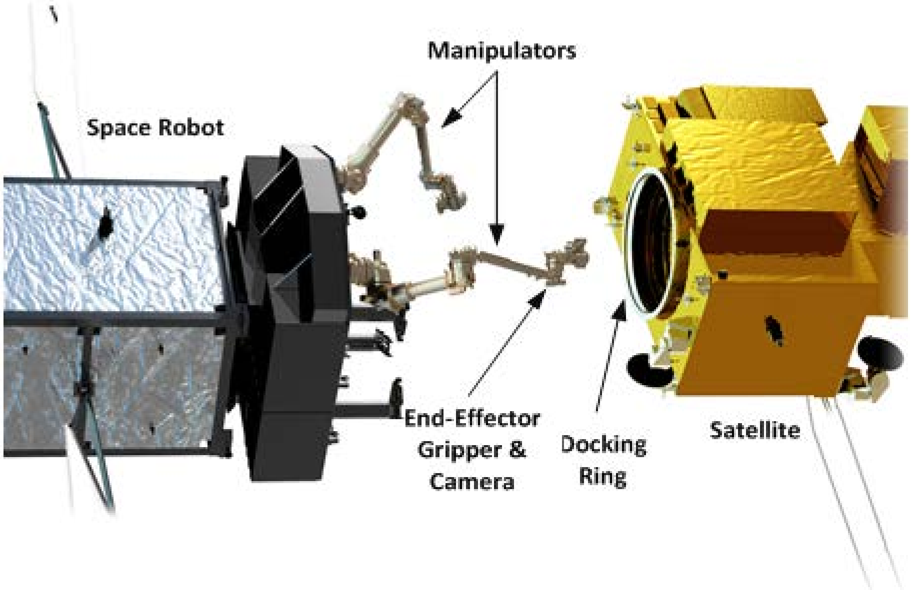


Figure 1 A concept of measuring and grasping the docking ring by Restore-L servicer

In this paper, a method based on single camera and double-line structured light is proposed to calculate the pose of a satellite using a docking ring component. The method only needs double line structured light and partial docking ring intersecting in the camera field of view. By using the constraint that the four intersection points are on the inner and outer circular features of partial docking ring, ambiguity is eliminated and the pose of the docking ring is calculated.

2. Pose Measurement Model

In final grasping, the distance is less than 0.5 meter. A single camera only obtains partial feature of large docking ring whose diameter is more than 1 meter. Therefore, a double-line structured light vision system is built to calculate pose by using the partial feature of large docking ring. Its measurement model is shown in Figure 2. Four measurement coordinate systems are defined, which are image coordinate system $o-uv$, camera coordinate system $O_C - {}^{C}X\,{}^{C}Y\,{}^{C}Z$, L1 line structured light coordinate system $O_{L1} - {}^{L1}X\,{}^{L1}Y\,{}^{L1}Z$ and L2 line structured light coordinate system $O_{L2} - {}^{L2}X\,{}^{L2}Y\,{}^{L2}Z$.

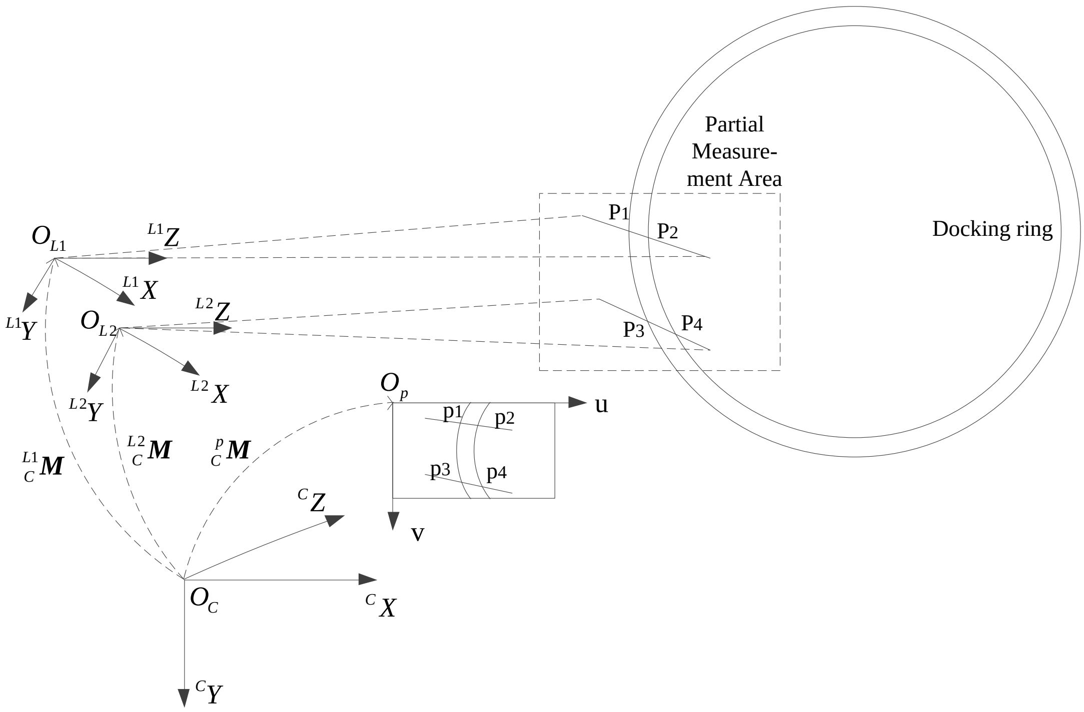


Figure 2 Measurement Model

In the image coordinate system, its point coordinate is $\boldsymbol{p} = [u, v, 1]^{\mathrm{T}}$. In the camera coordinate system, its point coordinate is ${}^{C}\boldsymbol{P} = [{}^{C}X, {}^{C}Y, {}^{C}Z]^{\mathrm{T}}$. The relationship between the camera coordinate system and the image coordinate system can be given by:

$$ {}^{C}Z\boldsymbol{p} = {}^{p}_{C}\boldsymbol{M}\,{}^{C}\boldsymbol{P} \tag{1}$$

${}^{p}_{C}\boldsymbol{M}$ is the camera intrinsic matrix, which can be given as:

$$ {}^{p}_{C}\boldsymbol{M} = \begin{bmatrix} f_u & 0 & u_0 \\ 0 & f_v & v_0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Where f_u and f_v are respectively normalized focal length in u and v axis, and (u_0, v_0) is the image centre coordinate. Matrix ${}^{p}_{C}\boldsymbol{M}$ can be determined by camera calibration in advance.

In the structured light coordinate system, the origin $O_{Li}(i=1,2)$ is located in the structure light emitting point. The ${}^{Li}Z(i=1,2)$ axis points to the line structure light transmitting direction, and the ${}^{Li}X(i=1,2)$ axis line structure light plane is perpendicular to the ${}^{Li}Z(i=1,2)$ axis. i.e. the plane of structure light is $O_{Li} - {}^{Li}X\,{}^{Li}Z(i=1,2)$. The point coordinate in this system is ${}^{Li}\boldsymbol{P} = [{}^{Li}X, {}^{Li}Y, {}^{Li}Z]^{\mathrm{T}}(i=1,2)$. The relationship between line structured light coordinate system and camera coordinate system can be given by:

$$ {}^{Li}\boldsymbol{P} = {}^{Li}_{C}\boldsymbol{R}\,{}^{C}\boldsymbol{P} + {}^{Li}_{C}\boldsymbol{T},\ (i=1,2) \tag{3}$$

${}^{Li}_{C}\boldsymbol{R}$ is rotation matrix, ${}^{Li}_{C}\boldsymbol{T}$ is translation matrix. We can have:

$$
{}^{Li}_{C}\boldsymbol{M} = \begin{bmatrix} {}^{Li}_{C}\boldsymbol{R} & {}^{Li}_{C}\boldsymbol{T} \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} {}^{Li}_{C}r_{11} & {}^{Li}_{C}r_{12} & {}^{Li}_{C}r_{13} & {}^{Li}_{C}T_{1} \\ {}^{Li}_{C}r_{21} & {}^{Li}_{C}r_{22} & {}^{Li}_{C}r_{23} & {}^{Li}_{C}T_{2} \\ {}^{Li}_{C}r_{31} & {}^{Li}_{C}r_{32} & {}^{Li}_{C}r_{33} & {}^{Li}_{C}T_{3} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}
$$

${}^{Li}_{C}\boldsymbol{M}$ is transformation matrix which can be calibrated in advance.

3. Pose Measurement Process

3.1. Pose Measurement Problem

By abstracting the docking ring component into single circular feature, pose parameters can be calculated including the coordinate of the circle centre and the unit normal vector of the circular plane under camera coordinate system. No matter how much the circular feature rotates around its normal vector, the image in the camera is constant, so there are only two attitude degrees of freedom can be determined without additional condition. However, in general pose measurement, it's enough to realize the tracking, approach and acquisition of the target spacecraft by using three position degrees of freedom and two attitude degrees of freedom that we obtain in this method.

In this paper, we use the definition of [10] to describe the unit normal vector of the circular plane $\boldsymbol{n} = [n_x, n_y, n_z]^{\mathrm{T}}$ with the pitch angle φ and the yaw angle θ. The angle between the $O_C - {}^{C}X\,{}^{C}Y$ plane and the plane normal vector is defined as pitch angle, while the angle between the projection of the normal vector on $O_C - {}^{C}X\,{}^{C}Y$ plane and the ${}^{C}X$ axis is defined as yaw angle. The relationship between the normal vector and the attitude angles can be given as:

$$
\begin{cases} \varphi = \arctan \dfrac{n_z}{\sqrt{n_x^2 + n_y^2}} \\ \theta = \arctan \dfrac{n_y}{n_z} \end{cases} \tag{5}
$$

Then, the relative pose parameters will be obtained including the coordinate of the centre $\boldsymbol{T} = [T_x, T_y, T_z]^{\mathrm{T}}$ and the attitude angles $[\varphi \quad \theta]$.

3.2. Pose Measurement Algorithm

The intersection points between structured light L1 and docking ring are $P_i (i = 1, 2)$. And the intersection points between structured light L2 and docking ring are $P_i (i = 3, 4)$. Their image coordinates $\boldsymbol{p}_i = [u_i, v_i, 1]^{\mathrm{T}}$ $(i = 1, 2, 3, 4)$ can be determined by image processing algorithm.

From (1), we have:

$$
{}^{C}X_i = \frac{u_i - u_0}{f_u}\,{}^{C}Z_i \quad (i = 1, 2, 3, 4) \tag{6}
$$

$$
{}^{C}Y_i = \frac{v_i - v_0}{f_v}\,{}^{C}Z_i \quad (i = 1, 2, 3, 4) \tag{7}
$$

In the structure light coordinate system, the plane equation of structure light is ${}^{Li}Y = 0$. From (3), the plane equation of structure light in the camera coordinate system is:

$$\begin{bmatrix} {}^{Li}_{C}r_{21} & {}^{Li}_{C}r_{22} & {}^{Li}_{C}r_{23} \end{bmatrix} {}^{C}\boldsymbol{P} + {}^{Li}_{C}T_{2} = 0, \quad (i = 1,2) \tag{8}$$

Using(6), (7) and(8), we can obtain the coordinates under the camera coordinate system ${}^{C}\boldsymbol{P}_{i} = [{}^{C}X_{i}, {}^{C}Y_{i}, {}^{C}Z_{i}, 1]^{\mathrm{T}}$ (i=1,2,3,4) .

Then, we have vectors:

$$\begin{cases} \overrightarrow{P_1P_4} = {}^{C}\boldsymbol{P}_4 - {}^{C}\boldsymbol{P}_1 \\ \overrightarrow{P_3P_2} = {}^{C}\boldsymbol{P}_2 - {}^{C}\boldsymbol{P}_3 \end{cases} \tag{9}$$

Because the vectors $\overrightarrow{P_1P_4}$ and $\overrightarrow{P_3P_2}$ are on the plane of docking ring and nonparallel, the unit normal vector of the plane is:

$$\boldsymbol{n} = \frac{\overrightarrow{P_3P_2} \times \overrightarrow{P_1P_4}}{\left| \overrightarrow{P_3P_2} \times \overrightarrow{P_1P_4} \right|} \tag{10}$$

And the attitude angles can be computed by(5).

In the following, the centre coordinate of docking ring will be calculated. As the same as (9), we have vectors:

$$\begin{cases} \overrightarrow{P_1P_3} = {}^{C}\boldsymbol{P}_3 - {}^{C}\boldsymbol{P}_1 \\ \overrightarrow{P_2P_4} = {}^{C}\boldsymbol{P}_4 - {}^{C}\boldsymbol{P}_2 \end{cases} \tag{11}$$

Because the centre of docking ring is on the mid-perpendicular of segment P_1P_3 and P_2P_4, we can have two line equations:

$$\boldsymbol{T}_1(t) = t(\overrightarrow{P_1P_3} \times \boldsymbol{n}) + \frac{{}^{C}\boldsymbol{P}_1 + {}^{C}\boldsymbol{P}_3}{2} \tag{12}$$

$$\boldsymbol{T}_2(t) = t(\overrightarrow{P_2P_4} \times \boldsymbol{n}) + \frac{{}^{C}\boldsymbol{P}_2 + {}^{C}\boldsymbol{P}_4}{2} \tag{13}$$

Where, t is parameter.

If the intersection angle between $\boldsymbol{T}_1(t)$ and $\boldsymbol{T}_2(t)$ is $\widehat{\boldsymbol{T}_1, \boldsymbol{T}_2} > 0$, the centre coordinate of docking ring will be the intersection point between $\boldsymbol{T}_1(t)$ and $\boldsymbol{T}_2(t)$, i.e.

$$\boldsymbol{T} = \left(\boldsymbol{T}_1(t), \boldsymbol{T}_2(t)\right) \tag{14}$$

The outer radius of docking ring will be:

$$R_{outer} = \left| {}^{C}\boldsymbol{P}_1 - \boldsymbol{T} \right| = \left| {}^{C}\boldsymbol{P}_3 - \boldsymbol{T} \right| \tag{15}$$

The inner radius of docking ring will be:

$$R_{inner} = \left| {}^{C}\boldsymbol{P}_2 - \boldsymbol{T} \right| = \left| {}^{C}\boldsymbol{P}_4 - \boldsymbol{T} \right| \tag{16}$$

If the intersection angle between $\boldsymbol{T}_1(t)$ and $\boldsymbol{T}_2(t)$ is $\widehat{\boldsymbol{T}_1, \boldsymbol{T}_2} \approx 0$ i.e. $\boldsymbol{T}_1(t)$ and $\boldsymbol{T}_2(t)$ are close to coincidence and singularity, the centre coordinate of docking ring will be:

$$\boldsymbol{T}=\sqrt{R_{outer}^2-\left(\left|{}^{C}\boldsymbol{P}_1-{}^{C}\boldsymbol{P}_3\right|^2/4\right)}\frac{\overrightarrow{P_1P_3}\times\boldsymbol{n}}{\left|\overrightarrow{P_1P_3}\times\boldsymbol{n}\right|}+\frac{{}^{C}\boldsymbol{P}_1+{}^{C}\boldsymbol{P}_3}{2}$$

$$or \qquad (17)$$

$$\boldsymbol{T}=\sqrt{R_{inner}^2-\left(\left|{}^{C}\boldsymbol{P}_2-{}^{C}\boldsymbol{P}_4\right|^2/4\right)}\frac{\overrightarrow{P_2P_4}\times\boldsymbol{n}}{\left|\overrightarrow{P_2P_4}\times\boldsymbol{n}\right|}+\frac{{}^{C}\boldsymbol{P}_2+{}^{C}\boldsymbol{P}_4}{2}$$

Until now, the relative position and attitude are all determined.

4. Simulation Study

In order to verify the effectiveness and robustness of the proposed method, the system is simulated under different error conditions, and the error analyses are performed. Sources of errors can be divided into two categories: the first category is called calibration errors, including the calibration errors of camera intrinsic matrix ${}^{P}_{C}\boldsymbol{M}$ and the calibration errors of line structured light installation matrix ${}^{Li}_{C}\boldsymbol{M}$. The second category is called input errors, which are the coordinate extraction errors of four intersection points between the double-line structured light and the partial docking ring.

Assuming that the double-line structured light L1 and L2 are separately installed above on the camera about 250*mm* and 200*mm*. And the angles between double-line structured light and camera optical axis are 20° and 30°. The image size of camera sensor is 1024×1024. The focus length of camera is 6mm. The physical pixel size of camera sensor is 3.75*um*. Then, two directions of normalized focal length α and β are both 1600. The coordinate of the image centre (u_0,v_0) is (512,512). The parameters of double-line structured light vision system are shown in Table 1.

Table 1 Parameters of Double-line Structured Light Vision System

Matrix	${}^{P}_{C}\boldsymbol{M}$	${}^{L1}_{C}\boldsymbol{M}$	${}^{L2}_{C}\boldsymbol{M}$
Parameter value	$\begin{bmatrix}1600 & 0 & 512\\ 0 & 1600 & 512\\ 0 & 0 & 1\end{bmatrix}$	$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 0.866 & 0.5 & -250\\ 0 & -0.5 & 0.866 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$	$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 0.939 & 0.342 & -200\\ 0 & -0.342 & 0.939 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$

For simulation, assuming that the outer radius of docking ring is 550*mm* and the inner radius of docking ring is 500*mm*.

According to the actual situation, the initial relative pose is set as:

$$\begin{cases}\left[\varphi \quad \theta\right]_{Initial}=\left[25^o \quad 20^o\right]\\ \left[T_x \quad T_y \quad T_z\right]=\left[600mm \quad 200mm \quad 500mm\right]\end{cases}$$

While the final relative pose is set as:

$$\begin{cases}\left[\varphi \quad \theta\right]_{Initial}=\left[5^o \quad 5^o\right]\\ \left[T_x \quad T_y \quad T_z\right]=\left[525mm \quad 20mm \quad 150mm\right]\end{cases}$$

After 100 measurement periods, the circular feature moves from the initial relative pose to the final relative pose at a constant speed.

Firstly, the calibration errors are simulated. For camera intrinsic matrix ${}_{C}^{p}\boldsymbol{M}$, Δf_u and Δf_v are errors of the normalized focal length, while ($\Delta u_0, \Delta v_0$) are errors of the image centre coordinate. For line structured light installation matrix, the rotation sequence of ${}_{C}^{Li}\boldsymbol{R}(i=1,2)$ is $Z \to X \to Y$, and the rotation angles are respectively γ_{Li} , α_{Li} and β_{Li} . $\Delta\gamma_{Li}$, $\Delta\alpha_{Li}$ and $\Delta\beta_{Li}$ are three-axis rotation errors respectively, while ΔZ_{Li} , ΔX_{Li} and ΔY_{Li} are three-axis translation errors respectively.

Secondly, the input errors are simulated. Assuming that the [$\Delta u_i, \Delta v_i$], (i=1,2,3,4) are the coordinate extraction errors of four intersection points between the double-line structured light and the docking ring.

In the following sections, the two error sources are analyzed separately to validate the pose measurement method.

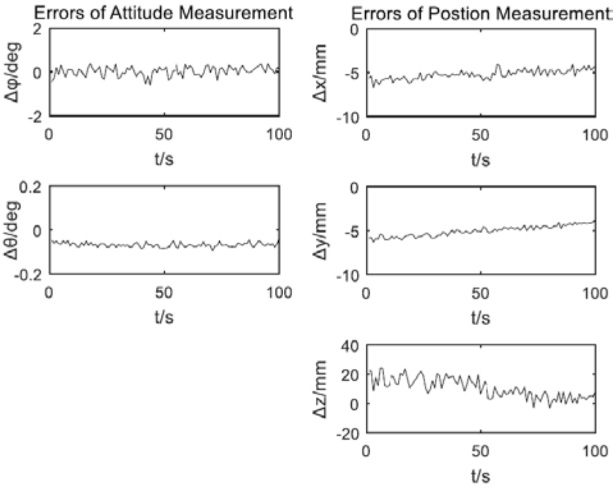
4.1. Errors of Calibration

According to the actual situation, the random errors of four intersection points $\Delta u_i \in [-2,2]$ and $\Delta v_i \in [-2,2]$ are introduced. On this basis, three typical calibration error combinations A1 ~A3 are designed as shown in Table 2. In the case of the three different combinations of errors, the system moves from the initial relative position and attitude to the final relative position and attitude at a constant speed in 100 periods.

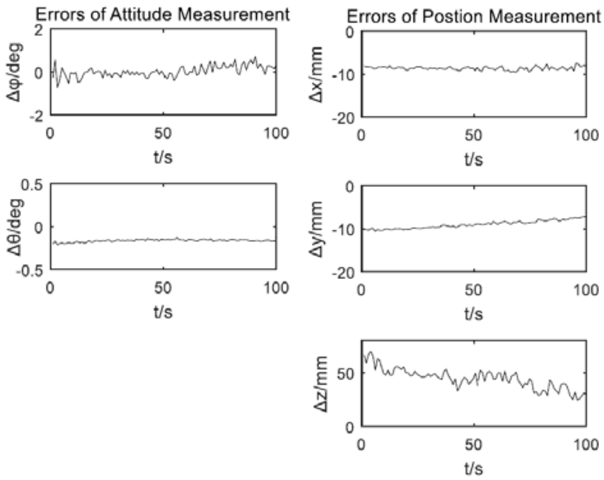
The measurement errors of the three cases are shown in Figure 3. From the results, the proposed method for pose measurement of non-cooperative docking ring based on double-line structured light is feasible. Errors of camera intrinsic matrix have small impact on attitude measurement but relatively large impact on position measurement. Calibration errors of line structured light have almost no impact on the accuracy of attitude measurement, but they have some effect on the position measurement.

Table 2 Calibration Error Combinations

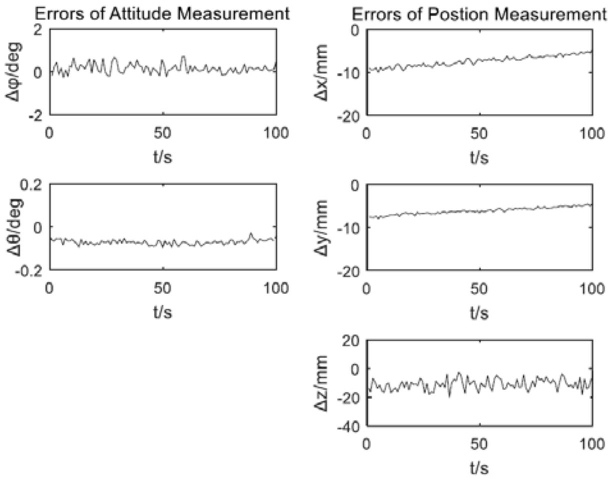
Calibration Errors	A1	A2	A3
$\Delta f_u, \Delta f_v$	10,10	20,20	10,10
$\Delta u_0, \Delta v_0$	5,5	10,10	5,5
$\Delta\alpha_{Li}, \Delta\beta_{Li}, \Delta\gamma_{Li}$ (°) (i=1,2)	0.1,0.1,0.1	0.1,0.1,0.1	0.2,0.2,0.2
$\Delta X_{Li}, \Delta Y_{Li}, \Delta Z_{Li}$ (mm) (i=1,2)	5,5,5	5,5,5	10,10,10



(a) Measurement Errors of Combination A1



(b) Measurement Errors of Combination A2



(c) Measurement Errors of Combination A3

Figure 3 Measurement Errors of Calibration

4.2. Random Errors of Inputs

On the basis of introducing the calibration error combination into the simulation, three typical input errors combinations B1~B3 are designed as shown in Table 3. The proposed algorithm is executed for 200 times in the initial relative pose statement with the three input error combinations respectively, and the maximum absolute measurement errors of case B1 ~B3 are shown in Table 4. From this table, the coordinate extraction errors of the four intersection points have some effect on the measurement of pitch angle, and they have relatively large effect on the measurement of Z axis.

Table 3 Input Random Error Combinations

Input Random Errors	B1	B2	B3
Δu_i, Δv_i (i=1,2,3,4)	[-1.0,1.0]	[-2.0,2.0]	[-4.0,4.0]

Table 4 Maximum Measurement Errors Caused by Input Errors

Measurement Errors	B1	B2	B3
$\Delta\varphi$	0.7396	0.7864	1.6058
$\Delta\theta$	0.0614	0.0846	0.1686
ΔT_x	6.9152	7.1526	8.4575
ΔT_y	6.0218	6.6429	7.2696
ΔT_z	22.6485	24.8463	32.1371

According to the results of the two numerical simulations, we can conclude that the proposed method for pose measurement of non-cooperative docking ring based on double-line structured light vision is feasible and effective. Camera calibration errors and the input errors of the two intersection points have relatively large effect on measurement accuracy. Reducing these two kinds of errors can significantly improve the accuracy of the position and attitude measurement.

5. Conclusions

In this paper, a method for pose measurement of non-cooperative docking ring based on double-line structured light vision is proposed. Using the four intersection points between the double-line structured light and partial docking ring, the method eliminates the ambiguity and calculates the position and attitude information of the circular plane docking ring. Compared with other pose measurement methods, the method doesn’t need the value of circular radius and has stronger robustness property. This paper gives the detailed process of the method and the simulation experiments under different error conditions, which fully verify the validity, practicality and accuracy of the method. The next step will build an actual physical simulation platform to take fully physical simulation and verification.

Acknowledgements

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