A positioning method of mobile manipulator based on binocular vision

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Abstract. This paper solves the problem of high-precision and flexible positioning of mobile manipulators. The target ball positioning tool is designed to be installed on the manipulator and calibrated. Then use binocular vision to locate the target ball positioning tool to realize the positioning of the mobile manipulator. The experimental measurement of the positioning accuracy is better than other positioning methods. The method of designing target ball positioning tool and adopting binocular vision positioning method has high precision and low cost.

Keywords: Binocular vision, Mobile manipulator, Position, Calibration.

1 Introduction

Positioning is a very important direction in the research of mobile manipulators, which determines whether the mobile manipulator can successfully complete the task. Mobile manipulator positioning includes mechanical positioning, two-dimensional code positioning [1] or ultrasonic positioning, lidar positioning [2] and so on. The positioning accuracy of mechanical positioning and QR code positioning is low, which is generally about 10mm, and is often located in a fixed position, which can't be located in any random position, which limits range of motion. The accuracy of ultrasonic positioning and lidar positioning is high, generally within 5mm, but the cost of positioning equipment is high.

Aiming at this problem, a positioning method of mobile manipulator based on binocular vision [3] is proposed in this paper. This method can realize high-precision positioning at low cost.

2 Positioning system

2.1 System components

The positioning system is mainly composed of a binocular camera and a target ball positioning tool installed at the end of the mobile manipulator.

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2.1.1 Binocular camera

Two sets of near-infrared cameras and near-infrared light sources constitute a binocular camera positioning system, which is installed on the binocular system bracket, and the included angle of the optical axis between the cameras is adjusted by a gimbal. The near-infrared filter can reduce the interference of ambient light, retain the required imaging of reflective markers, and improve the accuracy and stability of marker point identification.

2.2.2 Mobile manipulator

The mobile manipulator is composed of a three-degree-of-freedom mobile platform and a six-degree-of-freedom manipulator, with a total of nine degrees of freedom. The forward kinematics [4] operation is performed according to the structural parameters of the mobile manipulator, as shown in the following equation (1):

$$ {}^{m}_{6}T = {}^{m}_{0}T\,{}^{0}_{6}T = {}^{m}_{0}T\,{}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T\,{}^{3}_{4}T\,{}^{4}_{5}T\,{}^{5}_{6}T \tag{1} $$

${}^{m}_{0}T$ is the installation matrix of the manipulator base on the mobile platform, and ${}^{0}_{6}T$ is the pose matrix of the manipulator end relative to the base.

2.2.3 Target ball positioning tool

The target ball positioning tool adopts four reflective target balls to form features. Considering the end effector tool during the movement of the mobile manipulator, the target ball positioning tool is designed with general parts. No matter how the end effector tool is selected, the flange at the end of the manipulator does not change, so the connector is designed to be fixed on the flange of the outer ring, and the height position of the target ball tool is adjusted according to the end of the manipulator to prevent collision. As shown in figure 1 below:

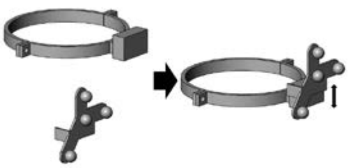


Fig. 1. Target ball positioning tool.

2.2 Positioning method

2.2.1 Solve target ball positioning tool pose

In order to accurately describe the pose of the target ball positioning tool, it is necessary to establish the target ball positioning tool coordinate system $\{O_t\}$ according to the four target balls. To establish a coordinate system, you first need to number the target balls.

As shown in figure 2, mark the numbers of the four target balls, $Ball_0, Ball_1, Ball_2, Ball_3$. The center direction of $Ball_1Ball_0$ is the positive direction of the X_t axis, and the center direction of $Ball_0Ball_2$ is the positive direction of the Y_t axis.

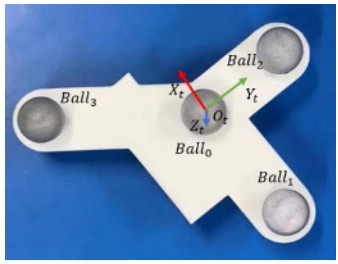


Fig. 2. Target ball number and coordinate system establishment on target ball positioning tool.

The distance between the four target balls is fixed. Assume that the three-dimensional coordinates of the four target balls are(x_1, y_1, z_1), (x_2, y_2, z_2), (x_3, y_3, z_3), (x_4, y_4, z_4). Then the constraints of the smallest cuboid in space on the X, Y and Z axes are shown in the following equation (2). Then remove the points on the boundary, and the last thing left is the coordinates of the center point $Ball_0$.

$$\begin{cases} x_{min} = \min(x_1, x_2, x_3, x_4)\,, x_{max} = \max(x_1, x_2, x_3, x_4) \\ y_{min} = \min(y_1, y_2, y_3, y_4)\,, y_{max} = \max(y_1, y_2, y_3, y_4) \\ z_{min} = \min(z_1, z_2, z_3, z_4)\,, z_{max} = \max(z_1, z_2, z_3, z_4) \end{cases} \tag{2}$$

The positions of the four target balls are calculated. The transformation matrix of $\{O_t\}$ relative to $\{O_{vw}\}$ is set to ${}^{vw}_{t}T$, ${}^{vw}_{t}T = [a, b, c, p]$. Where $a = (a_{11}, a_{12}, a_{13})^T, b = (b_{11}, b_{12}, b_{13})^T, c = (c_{11}, c_{12}, c_{13})^T$ are the visual system base system respectively $\{O_{vw}\}$ represents the unit vector of the three axes of the target ball positioning tool coordinate system X_t, Y_t, Z_t, and $p = (p_1, p_2, p_3)^T$ is the spatial position of the origin of $\{O_t\}$ under $\{O_{vw}\}$. Through $Ball_0^{vw}, Ball_1^{vw}$ point coordinates, the unit vector a on the O_tX_t axis can be obtained. The actual angle between $Ball_1Ball_0, Ball_0Ball_2$ may not be completely vertical, but the plane formed by them is regarded as the effective plane of $X_tO_tY_t$. The actual vectors b' of $Ball_0Ball_2$ and a calculate the unit vector c of the O_tZ_t axis. Finally, solve the unit vector b of the O_tY_t axis, as shown in equation (3):

$$\begin{cases} a = (a_{11}, a_{12}, a_{13})^T = norm[(x_1 - x_2, y_1 - y_2, z_1 - z_2)^T] \\ b' = (x_3 - x_1, y_3 - y_1, z_3 - z_1)^T \\ c = norm(a \times b') \\ b = a \times c \end{cases} \tag{3}$$

${}^{vw}_{t}T$ is obtained.

2.2.2 Tool calibration

By controlling the movement joints 5 and 6 of the manipulator, the spatial poses of multiple sets of target ball positioning tools are collected, and the installation parameter matrix ${}^{6}_{t}T$ of the target ball positioning tool is calculated using the variable data under the motion system. Let the initial rotation angle of the manipulator joint 5 be θ_{5_1}, and then the rotation angle after the movement is θ_{5_2}, then their rotation matrices are ${}^{4}_{5}T_1, {}^{4}_{5}T_2$. The initial rotation angle of joint 6 is θ_{6_1}, and then the rotation angle after movement is θ_{6_2}, then their rotation matrices are ${}^{5}_{6}T_1, {}^{5}_{6}T_2$ respectively. The positioning matrices of the target ball positioning tool before and after the movement of the binocular vision system are ${}^{vw}_{t}T_1$ and ${}^{vw}_{t}T_2$. The transformation matrix ${}^{1}_{2}A$ before and after the movement of the target ball positioning tool can be directly obtained, as shown in the following equation (4):

$$ {}_2^1A = ({}_t^{vw}T_1)^{-1} {}_t^{vw}T_2 \tag{4} $$

The pose of the mobile manipulator under the vision system combined with the kinematics of the mobile manipulator can be expressed as equation (5):

$$ {}_t^{vw}T = {}_m^{vw}T {}_6^mT {}_t^6T \tag{5} $$

Since other joints do not move except for joints 5 and 6, substitute equation (4) into equation (5) to obtain equation (6):

$$ {}_2^1A = ({}_t^6T)^{-1}({}_6^5T_1)^{-1}({}_5^4T_1)^{-1} {}_5^4T_2 {}_6^5T_2 {}_t^6T = ({}_t^6T)^{-1} M {}_t^6T \tag{6} $$

In equation (6), substitute the angle values at the beginning and end of the motion of the manipulator joints 5 and 6, and the known matrix $M = ({}_6^5T_1)^{-1}({}_5^4T_1)^{-1} {}_5^4T_2 {}_6^5T_2$. The actual installation matrix of the target ball positioning tool relative to the end of the manipulator is ${}_t^6T$, which can be further divided into theoretical installation matrix ${}_t^6T'$ and installation error matrix ${}_t^6T^w$. The theoretical installation matrix parameters are known.

$$ {}_2^1A = ({}_t^6T' {}_t^6T^w)^{-1} M ({}_t^6T' {}_t^6T^w) = ({}_t^6T^w)^{-1}[({}_t^6T')^{-1} M {}_t^6T'] {}_t^6T^w \tag{7} $$

In the error matrix ${}_t^6T^w$, the rotation angle around the X axis is α, the rotation angle around the Y axis is β, and the rotation angle around the Z axis is γ.

Measure the transformation matrix ${}_2^1A$ before and after the movement of multiple sets of target ball positioning tool, and substitute them into equation (7), solve the rotation angles α,β and γ by simultaneous equations. Finally get the actual installation matrix of the target ball positioning tool relative to the end of the manipulator ${}_t^6T = {}_t^6T' {}_t^6T^w$.

2.2.3 Position

The pose matrix ${}_t^{vw}T$ of the target ball tool coordinate system is located by the binocular vision system. The target ball positioning tool is installed at the end of the mobile manipulator and the installation pose matrix is ${}_t^6T$. The positioning of the end of the manipulator can be realized. According to the forward kinematics ${}_6^mT$ of the mobile manipulator, the positioning of the mobile platform is realized, as follows:

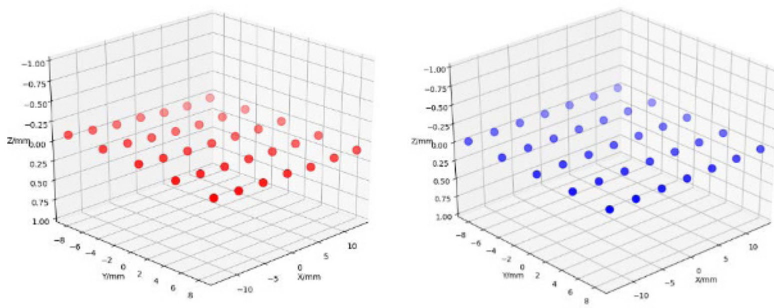
$$ \begin{cases} {}_6^{vw}T = {}_t^{vw}T({}_t^6T)^{-1} \\ {}_m^{vw}T = {}_6^{vw}T({}_6^mT)^{-1} \end{cases} \tag{8} $$

3 Experiment

3.1 Analysis of visual calibration

After the calibration of the left and right cameras is completed, another 15 sets of images are collected by the binocular camera, and the images are corrected respectively by the internal and external parameters saved by the single target. Then, according to the results of multiple sets of sampled data, the least squares method is used to fit the best results to obtain stable calibration results.

As shown in the figure 3 above, the average error of the coordinate deviation between the corresponding points is used as the accuracy evaluation standard, and the error value ε=0.67mm between the actual measurement value and the theoretical position is calculated.



(a) Calibration results (b) Theoretical value

Fig. 3. Comparison between the calibration results the theoretical values.

3.2 Analysis of tool calibration

The relative pose measurement of the target ball positioning tool and the end of the manipulator was carried out through the portable three-coordinate of the FAROARM measuring arm, and the measurement data and the calibration data were compared to evaluate the calibration. As shown in table 1 below:

Table 1. Comparison of measurement data and calibration data.

Parameters	$x[mm]$	$y[mm]$	$z[mm]$	$\alpha[°]$	$\beta[°]$	$\gamma[°]$
Measure Data	−120.4205	−0.515	194.1163	3.9241	1.6543	3.3307
Calibration Data	−121.7913	−0.8513	195.4779	4.0181	1.623	3.3205
Error	1.3708	0.3363	1.3616	0.094	0.0313	0.0102

The error of the tool center position in the x, y and z directions is within 1.5mm, and the comprehensive distance error is 1.96mm. The rotation angle errors on both the y and z axes are within 0.1°. In addition to the error of the binocular vision system, ε=0.67mm, the positioning error of the binocular vision system used in this paper is limited to less than 3mm, which is smaller than the error value of the traditional positioning method.

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