Agent Collaboration Technology Based on Multi-camera Pose Monitoring System

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Abstract: Multi-camera pose monitoring system is a high precision digital measuring equipment which can be used to obtain the three-dimensional position information of the target in environment. We constructed a new agent system consisting of many Mecanum wheel mobile robots and multi-camera pose monitoring system, which can be divided into three parts: positioning subsystem, communication subsystem and control subsystem. First, the multi-camera system acts as a positioning system to locate the agent through the reflective target balls, then the communication subsystem sends large positioning information to the control subsystem in real time. The control subsystem identifies different agents, and converts the pose relationship under the camera coordinate system to the world coordinate system. Finally, according to the position relationship between different agents, the corresponding cooperative control algorithm is designed to solve the input parameters required by a single agent, and control the agent to reach the specified position precisely. The experiment results show that the agent positioning assisted by the multi-camera pose monitoring system has small positioning error, which can make the whole agent cluster have good cooperative control performance.

Key words: multi-camera pose monitoring system; agent cooperative control; dynamic trajectory tracking

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0 Introduction

The positioning accuracy of each agent node is the most basic link in the cooperative control of agent cooperation. It is generally required that the positioning accuracy of the agent is at the centimeter level indoors. Indoor positioning technologies generally include relative positioning based on encoder and inertial sensor, WiFi positioning, wireless radio frequency tag positioning (RFID), ultra-wideband positioning (UWB), and ZigBee positioning. Ref.[1] based on the positioning technology combined with dead reckoning and radio frequency identification technology, the positioning error of the robot is controlled within 20 cm; asymmetric double-sided two-way ranging (ADS-TWR) based on UWB technology and Kalman filtering are adopted for positioning, the positioning error is within 13 cm[2]; Ref.[3] studies the trilateral positioning of mobile robots based on ZigBee technology, the positioning error is between 5 cm and 7 cm, but when the robot is within 30 cm from the fixed node, it cannot be positioned. It can be concluded that the above positioning methods still have problems, such as insufficient positioning accuracy and positioning range. However, the multi-camera pose monitoring system based on reflective marker points can achieve sub-millimeter positioning accuracy. The field of view that can be positioned can also be dynamically expanded depending on the number of cameras and the type of lens. The low delay and real-time performance meet the high-speed response for agent cooperation. Therefore, this paper uses the multi-camera monitoring technology to locate each node of the agent.

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For the trajectory tracking algorithm design of agent cooperation, it is necessary to explore the motion control method of single agent and the cooperative control strategy of agent cluster. For the control of single agent, the common methods include PID control[4], adaptive control[5], sliding mode control[6], neural network method[7], and fuzzy control[8]. Considering that the design of the controller needs to satisfy three demands: (1) It can ensure the stability of the system. (2) It can adjust the working parameters in different speed range. (3) It can give feedback to external disturbances in time to achieve real-time online regulation. So, we adopt the classical proportional-integral-derivative (PID) control method. The cooperative control strategies can be divided into the followings[9]: Leader-follower control method, behavior based control method, reinforcement learning control method, and virtual structure method. In this paper, the control algorithm is studied based on leader-follower method, and the position information of the leader, follower and target point is obtained by multi-camera system. The distance error and angle error between the navigator and the follower are calculated according to the formation. The speed and direction of the follower are calculated so that it is always in line with the navigator, thereby maintaining control of the formation.

1 Principle of Multi-camera Pose Monitoring

The real-time multi-camera pose monitoring system is a motion capture system based on reflection. It needs to paste a kind of reflective ball on the captured agent in advance. When the red light emitted by the camera hits the surface of the reflective ball, the reflective ball will reflect the same wavelength of red light to the camera, so that the camera can determine the 2D coordinates of each reflective ball, and get its 3D coordinates after being processed by the software of the multi-camera system. And because the cameras of the multi-camera system are all high-speed and high-resolution, the motion trajectory of each reflective ball can be clearly recorded to obtain the tracking data.

1.1 Multi-camera 3D reconstruction

According to the basic principle of three-dimensional reconstruction, a single view cannot recover the depth information of the space, and at least two or more views are required to recover the spatial information of the target point. In large field of vision measurement, the target to be measured is relatively small. It is difficult to accurately measure the 3D coordinates of the target with only two views, so three views or multi-views are born to reconstruct the target, as shown in Fig.1.

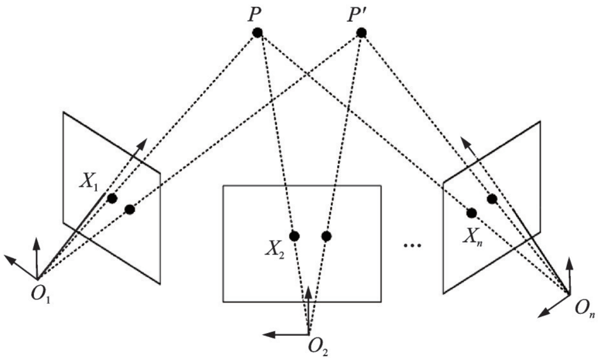

Fig.1 Position relationship between multi-camera image points and space

Suppose there are n cameras, and the projections of point P in space on the image plane of each camera are X_1, X_2, X_3, $\cdots$, X_n, according to the triangulation of two views, the functions is

$$\begin{bmatrix} v_1 \boldsymbol{P}_{13} - \boldsymbol{P}_{13} \\ \boldsymbol{P}_{11} - u_1 \boldsymbol{P}_{13} \\ v_2 \boldsymbol{P}_{23} - \boldsymbol{P}_{22} \\ \boldsymbol{P}_{21} - u_2 \boldsymbol{P}_{23} \\ \vdots \\ v_n \boldsymbol{P}_{n3} - \boldsymbol{P}_{n2} \\ \boldsymbol{P}_{n1} - u_n \boldsymbol{P}_{n3} \end{bmatrix} \tilde{P} = 0 \tag{1}$$

where (v_i, u_i) is the pixel coordinates of image point X_i, $\boldsymbol{P}_{ij}$ the jth row of the ith camera projection matrix, and $\tilde{P}$ the homogeneous coordinate of the space point. When the camera system has been calibrated and n cameras simultaneously observe a certain spatial point, $2n$ constraint equations can be formed. The coefficient matrix of the equation is set to $\boldsymbol{A}$, and the solution of the overdetermined equation can be obtained by singular value decomposition of $\boldsymbol{A}$, that is, the 3D coordinates of the space point.

1.2 Multi-camera image point matching based on epipolar constraints

In the process of pose tracking, the key of reflective target reconstruction is to establish the matching relationship of image points. The idea of epipolar geometry is often used to solve this kind of problem. The concept of epipolar geometry is that the projection of the connecting line between an image point and a space point in another view is the epipolar line of the image point, thus, an image point in one view corresponds to a epipolar line in another view. Its advantage is that the search range of corresponding points can be reduced by using the epipolar constraint. But in fact, due to the influence of noise and other factors, the corresponding point is not just on this epipolar line, but near this polar line. Therefore, the distance from the matching point to the epipolar line can be calculated to determine whether the point is a corresponding point.

First, determine the basic matrix between the two views. The basic matrix $\boldsymbol{F}=\boldsymbol{K}'^{-1}\boldsymbol{RSK}^{-1}$, where $\boldsymbol{K}$ and $\boldsymbol{K}'$ are the internal parameter matrices of the two cameras; $\boldsymbol{R}$ is the rotation matrix between the two cameras and $\boldsymbol{S}$ the anti-symmetric matrix of the translation vecter corresponding to the two cameras. Supposed that the internal parameters of the camera are known, it is necessary to calculate the pose relationship between each camera according to the pose relationship between the camera and the world coordinate system. The rotation matrix and translation vector of the two cameras relative to the world coordinate system are set to $\boldsymbol{R}_1, \boldsymbol{R}_2, \boldsymbol{t}_1, \boldsymbol{t}_2$. According to the coordinate conversion relationship, the functions are

$$\begin{cases} \boldsymbol{P}_1=\boldsymbol{R}_1\boldsymbol{P}+\boldsymbol{t}_1 \\ \boldsymbol{P}_2=\boldsymbol{R}_2\boldsymbol{P}+\boldsymbol{t}_2 \end{cases} \tag{2}$$

where $\boldsymbol{P}$ is a point in space, $\boldsymbol{P}_1, \boldsymbol{P}_2$ are the coordinates of the space point in the two cameras coordinate system. The rotation matrix and translation vector of the two cameras are $\boldsymbol{R}_{12}$ and $\boldsymbol{t}_{12}$, then $\boldsymbol{P}_2=\boldsymbol{R}_{12}\boldsymbol{P}_1$. Bring it into Eq.(2) , there is $\boldsymbol{R}_2\boldsymbol{P}+\boldsymbol{t}_2=\boldsymbol{R}_{12}\boldsymbol{R}_1\boldsymbol{P}+\boldsymbol{R}_{12}\boldsymbol{t}_1+\boldsymbol{t}_{12}$, and the pose of the two cameras has the following form

$$\begin{cases} \boldsymbol{R}_{12}=\boldsymbol{R}_2\boldsymbol{R}_1^{-1} \\ \boldsymbol{t}_{12}=\boldsymbol{t}_2-\boldsymbol{R}_{12}\boldsymbol{t}_1 \end{cases} \tag{3}$$

After the pose relationship between the two cameras is obtained, the basic matrix can be calculated according to $\boldsymbol{F}_{12}=\boldsymbol{K}_2^{-\mathrm{T}}\boldsymbol{R}_{12}\boldsymbol{S}_{12}\boldsymbol{K}_1^{-1}$, where $\boldsymbol{S}_{12}$ is the anti-symmetric matrix corresponding to the translation vecter $\boldsymbol{t}_{12}$. Then the epipolar lines of the two views can be calculated by

$$\begin{cases} \boldsymbol{l}_1=\boldsymbol{F}_{12}^{\mathrm{T}}\boldsymbol{x}_2=[A_1 \;\; B_1 \;\; C_1]^{\mathrm{T}} \\ \boldsymbol{l}_2=\boldsymbol{F}_{12}\boldsymbol{x}_1=[A_2 \;\; B_2 \;\; C_2]^{\mathrm{T}} \end{cases} \tag{4}$$

where $\boldsymbol{x}_1, \boldsymbol{x}_2$ are the coordinates of the space point in the two image, and $\boldsymbol{A}, \boldsymbol{B}$, and $\boldsymbol{C}$ the parameters of the linear equation. After obtaining the epipolar line of a certain point in another image, the corresponding points can be screened according to the distance from the image point to the epipolar line.

$$\boldsymbol{d}=\frac{|\boldsymbol{A}\boldsymbol{u}+\boldsymbol{B}\boldsymbol{v}+\boldsymbol{C}|}{\sqrt{\boldsymbol{A}^2+\boldsymbol{B}^2}} \tag{5}$$

Traverse the image points of another view. When the distance from the image point to the epipolar line is less than the predefined threshold, it is considered as a candidate point.

Multi-view epipolar constraint image point matching is to number the image points in each view based on the above principles, and establish their own lookup tables for the image points in different views according to the different numbers, find the corresponding relationships of the image points in each view based on the epipolar constraint principle, update the image point sequence, and reconstruct the spatial coordinates of all targets.

If the measured object is a rigid body, paste at least three non-collinear reflective target balls on the measured object, and then establish a kinematic model according to the position of the reflective marker balls. Through the recognition and tracking of the model, the pose information of the rigid body can be obtained in real time.

2 Design of Agent Controller

2.1 Motion model establishment

In this paper, Mecanun wheel mobile robot and human are specific research agents to realize human-machine following. The mobile robot can move in all directions with three degrees of freedom, namely translation along the x and y axes and rotation around the z axis, as shown in Fig.2. The included angle between the hub axis and the roller axis is 45°. The overall layout is shown in the figure. The local coordinate system xyz is established on the mobile robot according to the position of the reflective target ball.

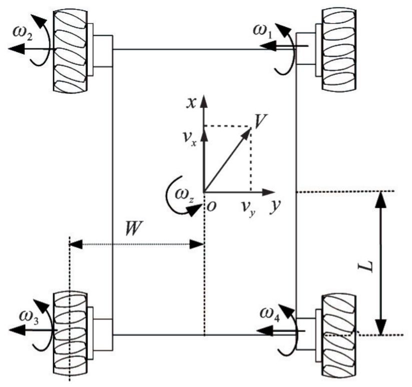

Fig.2 Omnidirectional mobile robot diagram

It is assumed that the Mecanun wheel is in full contact with the ground and there is no slip, and the center of gravity of the mobile robot platform coincides with the geometric center. By analyzing the relationship between the vehicle body speed and the wheel speed of the mobile robot[10], the forward kinematics equation of the omnidirectional mobile robot can be obtained as follows

$$\begin{cases} \dot{\boldsymbol{q}} = \boldsymbol{J}\dot{\boldsymbol{\Theta}} \\ \boldsymbol{J} = \dfrac{R}{4}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ -\dfrac{1}{W+L} & \dfrac{1}{W+L} & -\dfrac{1}{W+L} & \dfrac{1}{W+L} \end{bmatrix} \end{cases} \tag{6}$$

where $\dot{\boldsymbol{q}} = [\boldsymbol{v}_x, \boldsymbol{v}_y, \boldsymbol{\omega}_z]^{\mathrm{T}}$ is the speed of the mobile robot in the global coordinate system, $\dot{\boldsymbol{\Theta}} = [\boldsymbol{\omega}_1, \boldsymbol{\omega}_2, \boldsymbol{\omega}_3, \boldsymbol{\omega}_4]^{\mathrm{T}}$ the angular velocity of the mobile robot in the local coordinate system, $\boldsymbol{J}$ the Jacobian matrix between the platform speed and the wheel speed, and R the wheel radius; W and L are the horizontal and vertical distances between the central axis and point, respectively. According to the generalized inverse operation, the inverse kinematics equation of the mobile robot can be obtained as follows

$$\dot{\boldsymbol{\Theta}} = \boldsymbol{J}^{+}\dot{\boldsymbol{q}} \tag{7}$$

where $\boldsymbol{J}^{+}$ is the generalized inverse matrix of Jacobian matrix.

2.2 Position and orientation model

The design of human-machine following controller of the agent is based on the position and orientation model, and the goal is to make the error converge to 0 by using the controller. The motion of the mobile robot considered in this paper only considers on two-dimensional plane, that is, the movement of z-axis direction is not considered, as shown in Fig.3. Then the actual pose $\boldsymbol{M}$ of the agent in global coordinate system can be expressed as $\boldsymbol{M} = [x \;\; y \;\; \theta]^{\mathrm{T}}$.

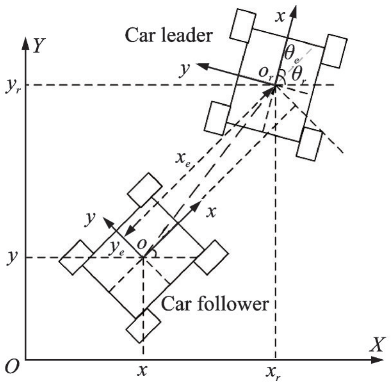

Fig.3 Pose description diagram

Suppose there is a navigator and a follower on the two-dimensional plane, the kinematic model of the navigator is

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \boldsymbol{v} \\ \boldsymbol{\omega} \end{bmatrix} \tag{8}$$

and the velocity formula is expanded as

$$\begin{cases} \dot{x} = \cos\theta \cdot \boldsymbol{v} \\ \dot{y} = \sin\theta \cdot \boldsymbol{v} \\ \dot{\theta} = \boldsymbol{\omega} \end{cases} \tag{9}$$

$\boldsymbol{E}_{(t)}^{\mathrm{T}}$ is the global pose error between the navigator and the follower and $\boldsymbol{e}_{(t)}^{\mathrm{T}}$ the pose error in local coordinate system. The relationship between them is

$$\boldsymbol{e}_{(t)}^{\mathrm{T}} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 \end{bmatrix} \boldsymbol{E}_{(t)}^{\mathrm{T}} \tag{10}$$

which is equivalent to

$$\begin{bmatrix} x_e \\ y_e \\ \theta_e \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_r - x \\ y_r - y \\ \theta_r - \theta \end{bmatrix} \tag{11}$$

Set the speed of the mobile robot in the local coordinate system as $\boldsymbol{v}_x$, and the corresponding mobile robot in the global coordinate system as $\boldsymbol{v}$, that is, $\boldsymbol{v}_x = \boldsymbol{v}$, $\boldsymbol{v}_y = 0$. The velocity along the x-axis $\boldsymbol{v}_x$ and y-axis $\boldsymbol{v}_y$ can be synthesized as $\boldsymbol{v}$, where $\boldsymbol{v}_x = \boldsymbol{v}\cos\theta$, $\boldsymbol{v}_y = \boldsymbol{v}\sin\theta$. By differentiating the formula

$$\begin{cases} \dot{x}_e = \boldsymbol{\omega} y_e - \boldsymbol{v} + \boldsymbol{v}_r \cos\theta_e \\ \dot{y}_e = -\boldsymbol{\omega} x_e - \boldsymbol{v}_r \sin\theta_e \\ \dot{\theta} = \boldsymbol{\omega}_r - \boldsymbol{\omega} \end{cases} \tag{12}$$

In the process $t \to \infty$, the speed of the agent decreases continuously. The virtual coordinate system is established in the process of human-machine following control, and the follower follows the virtual coordinate system so that a fixed distance and angle between the follower agent and the navigator human can be maintained to achieve the purpose of team cooperation.

2.3 Design of controller model

The input value of agent cooperative controller is the position and orientation of all agents under multi-camera monitoring system. A reference coordinate system is established for each agent in the controller. Calculate the real-time pose relationship between all coordinate systems in the monitoring field, and the pose errors between any agent and the target can be calculated, thereby obtaining the desired linear velocity and angular velocity of the agent. Finally, the pose of the agent is collected and fed back to the controller in real time. The controller is adjusted repeatedly according to this process so that the pose errors of the following agent tends to zero. The process is shown in Fig.4.

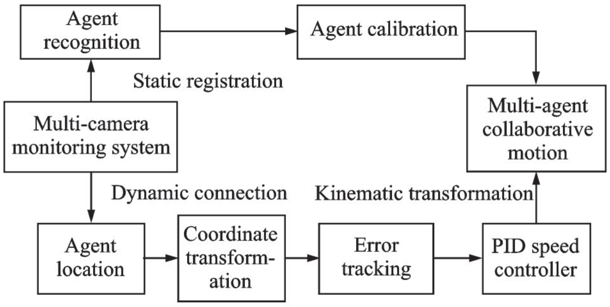

Fig.4 Trajectory tracking system structure

PID global control function is established to adjust the distance error of input control system.

$$\boldsymbol{V}_A(t) = k_{\mathrm{P}} \boldsymbol{e}_{(\mathrm{t})}^{\mathrm{T}} + k_{\mathrm{D}} \frac{\mathrm{d}\boldsymbol{e}_{(\mathrm{t})}^{\mathrm{T}}}{\mathrm{d}t} + k_{\mathrm{I}} \int_0^t \boldsymbol{e}_{(\mathrm{t})}^{\mathrm{T}} \mathrm{d}t \tag{13}$$

where k_{P}, k_{D} and k_{I} are the adjustment parameters, and the speed controller can be designed as follows

$$\begin{cases} \boldsymbol{v}_x = k_{\mathrm{P}}(\cos\theta(x_r - x) + \sin\theta(y_r - y)) + \\ \qquad k_{\mathrm{D}}(\boldsymbol{\omega} y_e - \boldsymbol{v} + \boldsymbol{v}_r \cos\theta_e) + k_{\mathrm{I}} \int_0^t (\cos\theta(x_r - x) + \\ \qquad \sin\theta(y_r - y))\mathrm{d}t \\ \boldsymbol{v}_y = k_{\mathrm{P}}(-\sin\theta(x_r - x) + \cos\theta(y_r - y)) + k_{\mathrm{D}}(-\boldsymbol{\omega} x_e - \boldsymbol{v}_r \sin\theta_e) + \\ \qquad k_{\mathrm{I}} \int_0^t (-\sin\theta(x_r - x) + \cos\theta(y_r - y))\mathrm{d}t \\ \boldsymbol{\omega} = k_{\mathrm{P}}(\boldsymbol{\theta}_r - \boldsymbol{\theta}) + k_{\mathrm{D}}(\boldsymbol{\omega}_r - \boldsymbol{\omega}) + k_{\mathrm{I}} \int_0^t (\boldsymbol{\theta}_r - \boldsymbol{\theta})\mathrm{d}t \end{cases} \tag{14}$$

3 Construction of Test Platform

The hardware equipment in the experimental environment includes twelve 5-megapixel digital cameras, a PC that controls multiple cameras to trigger and collect data synchronously, a console PC that assists agent cooperative decision-making, and two smart cars with independent master control. The entire test environment is shown in the Fig.5.

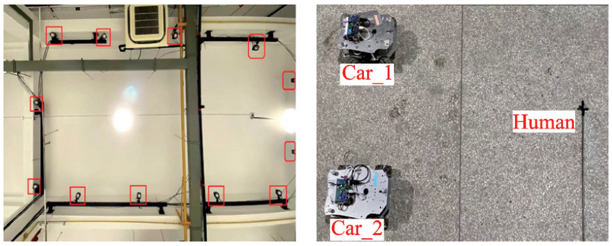

Fig.5 Experimental environment diagram

In the whole system, in order to control the cooperative movement of agents, it is necessary to know the position and orientation of each agent. Therefore, reflective target balls are placed on the agent in different arrangements. The reflective target balls are rigidly connected with the agent. The multi-camera system can track the position information of the geometric center of each reflective target ball in real time, which is the basis of the agent's position and orientation calculation. Then a global communication network for the whole system and a TCP/IP[11] wireless communication between PC1 and PC2 are established. PC1 is set as the server, and PC2 is set as the client, which is used to transmit a large number of position and orientation data of the reflective target ball. A node communication based on RosMaster[12] between the PC2 and each mobile robot is established, the leader agent is set as the host, and other following agents are set as the slave. The relative pose relationship between mobile robots is published in the form of a topic, and the slave subscribes the topic as the input of the cooperative controller. The mobile agent uses discrete PID to determine the desired speed according to the real-time collected pose data, and sends it to the main control board through the high-speed serial port. After receiving the data, the main control board converts it into the expected speed of four motors through kinematics equations, and sends it to the motor controller via CAN bus. The motor controller regulates the speed of the DC motor in real time, and the motor drives the mecanum wheel to realize the movement of the entire mobile robot, as shown in Fig.6.

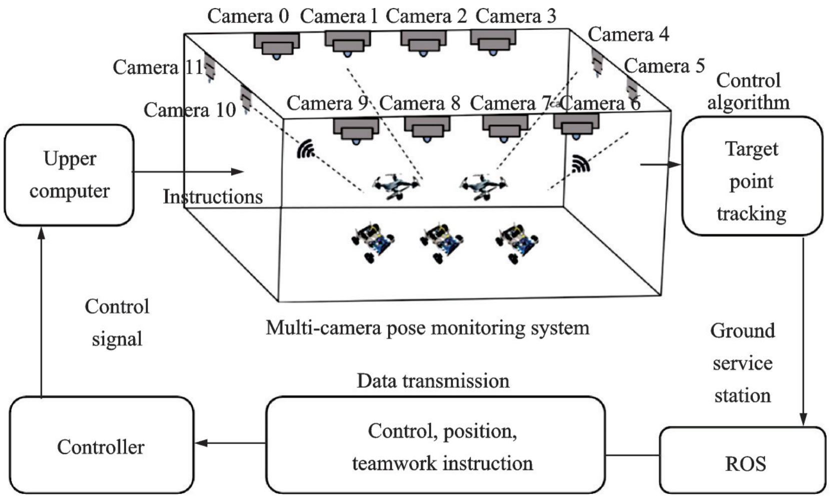

Fig.6 Multi-camera pose monitoring system

4 Experimental Results and Analysis

The experimental environment consists of hardware and software. The hardware part includes twelve optical cameras, twelve infrared lights installed on the camera, a control board that controls the synchronous trigger of the camera and the infrared light, two mobile vehicles, and a calibration rod. The software includes a self-developed control multi-camera data acquisition, target tracking measurement system, and a control platform for controlling multi-body coordinated motion.

The experimental design of this paper is mainly to test the following contents: (1) The accuracy of the agent position and orientation monitored by the multi-camera system; (2) performance of the target tracking control algorithm.

4.1 Positioning accuracy of multi-camera system

In order to evaluate the accuracy of the target positioning in multi-camera monitoring system, the calibration rod is randomly moved in the measurement field to measure the distance between two pairs of three points on the calibration rod. The experimental results are shown in Table 1. Comparing the actual length of the calibration rod with the measuring length, the average absolute error of the whole measuring system is less than 0.3 mm.

Table 1 Results of positioning accuracy mm

Symbol	Actual length	Average measuring length	Mean absolute error	Standard deviation
AB	199.804	199.657	0.262	0.353
CD	100.153	100.074	0.101	0.119

4.2 Human-machine dynamic trajectory tracking verification

The human-machine trajectory tracking experiment is carried out under the condition that the target and the follow mobile robot has been identified in advance. The experiment results are shown in Fig.7. The camera frame rate is 30, $k_{\mathrm{P}}=0.000\ 1$, $k_{\mathrm{I}}=000\ 000\ 1$, and $k_{\mathrm{D}}=0.001$. The robot follows the target at a speed of 2 m/s.

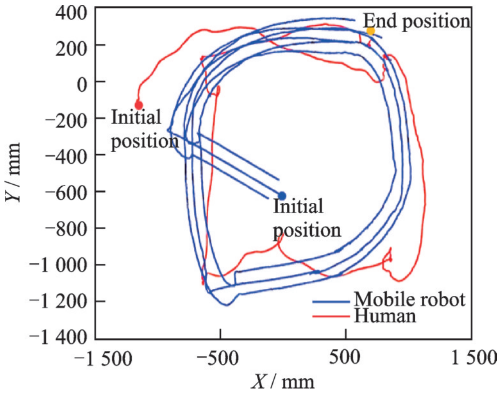

Fig.7 Mobile robot follows human diagram

It can be analyzed that different PID parameters can influence the tracking performance. It necessary to select appropriate parameters according to the specific environment. Meanwhile, due to the wheel slip of the mobile robot, there is a deviation between the actual track and the expected track, but the deviation is small, which does not affect the actual tracking results. It has proved that the trajectory tracking algorithm can achieve good tracking towards dynamic objects.

5 Conclusions

We independently developed a multi-camera position and orientation monitoring system with twelve cameras. The system tracks and locates the agents based on the reflective target ball in real time, and takes the acquired data as the input to the agent controller. A human-machine cooperative controller for trajectory tracking is designed and verified by virtual simulation and self-built experimental platform. The results show that the position and orientation monitoring system based on the reflective target ball provides an effective means for indoor agent cooperative work. By designing a stable human-machine cooperative controller and selecting appropriate parameters, good track tracking performance, high cooperative control accuracy, and real-time performance can be obtained.

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Author contributions Ms. **ZHOU Ling** and Ms. **WANG Anqi** contributed to the conceptulization, designed the methodolgy, conducted the validation and formal analysis, and wrote the manuscript. Mr. **WU Linpeng** took part in the software development of the multiview monitering system. Prof. **ZHANG Liyan** supervised the research. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: XU Chengting)

基于多目位姿实时监测的多体协同技术研究

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摘要：多目位姿实时监测系统是一种高精度的数字化测量设备，可用于获取目标物在空间中三维位置信息。本文将多个麦克纳姆移动机器人和多目视觉系统相结合构建智能体集群系统，该系统由定位子系统、通信子系统、控制子系统3部分组成。多目视觉系统作为定位系统通过反光靶球对智能体进行定位，通信子系统将定位信息实时输入控制子系统，控制子系统识别不同的智能体，并将相机坐标系下位姿关系转换到世界坐标系下，再根据不同智能体彼此间的位置关系，设计相应的协同控制算法解算单个智能体所需的姿态控制输入，控制智能体达到指定的位置。测试结果表明，用多目位姿实时监测系统辅助多智能体定位，定位误差小，可令整个智能体集群拥有良好的协同控制性能。

关键词：多目位姿实时监测系统；多智能体协同控制；动态轨迹跟踪