# Multirobot Cooperative Localization Based on Visible Light Positioning and Odometer

Zihong Yan, Weipeng Guan, Shangsheng Wen, Linyi Huang, and Hongzhan Song

***Abstract*—With the development of robotics, multirobot collaboration system (MRCS) has become a popular focus of research in recent years. As the key technology of MRCS, multirobot cooperative localization (MRCL) is becoming more and more popular due to its higher accuracy and robustness by exchanging and sharing information. In this article, we propose an MRCL system based on visible light positioning (VLP) technology and odometer (VO-MRCL). Using rolling shutter camera and odometer, the system relaxes the quantity required for observable-light emitting diode (LED) lamps of each robot to one and improves the robustness of the VLP-based robot positioning methods under LED shortage. The accuracy of the proposed VO-MRCL system is verified by real-world experiments, where a two-robot system is proposed as an example specifically. The results of experiment show that our proposed system is feasible and can achieve the positioning accuracy with an average error of 4.31 cm.**

***Index Terms*—Cooperative localization, multirobot, odometer, robotic localization, visible light positioning (VLP).**

## I. INTRODUCTION

ROBOTICS localization is one of the most essential capabilities and basic premise for many other functions of robots, especially with the increasing demand for indoor service robots, indoor localization-based services, indoor parking, and so on. Impacted by multipath reflections and penetration capability, global positioning system (GPS) is not available in indoor environment [1]. Conventional indoor positioning technologies such as radio frequency identification, Bluetooth, ZigBee, Wi-Fi, and ultrasonic often do not satisfy the desired level of accuracy, reliability, implementation cost, or simplicity [2]. With the development of light-emitting diodes (LEDs) and visible light communication (VLC), visible light positioning (VLP) realizes indoor positioning of the receivers through position information transmitted by LED lamps modulated at a high frequency which is invisible to human eyes. In contrast to the conventional indoor positioning technologies, VLP technology has the advantages of high accuracy, no electromagnetic interference, and low cost of implementation [3], which is becoming a promising solution to indoor positioning.

VLP technology falls into two categories based on receiver type, the photodiode-based (PD) [4] and the camera-based [5]–[8]. In [4], a VLP system based on PD using the particle swarm optimization algorithm is proposed and it can achieve centimeter (cm)-level accuracy with four LEDs. In [5], a real-time VLP system with lightweight image processing algorithm using double LEDs is proposed, which achieves a positioning accuracy of 3.93 cm with a moving speed up to 38.5 km/h. In [6] and [7], VLP algorithms based on triple, double LEDs are proposed and realize cm-level accuracy. In [8], an angle-of-arrival localization algorithm based on camera using three or more LEDs is proposed and it can achieve decimeter-level accuracy. Although the VLP-based localization methods in the literature can achieve decimeter-level or even cm-level accuracy, two or more LED anchors are needed to realize localization, which results in high-density deployments of LED anchors. Therefore, it may easily lead to positioning failure in harsh environment. For example, if only one LED can be detected on account of LED shortage such as signal missing or obstacles blocking. Therefore, methods have been researched to solve the bottleneck of VLP such as using beacon-attached LED [9]–[11], sensors combination [1], [12]–[16], or cooperative localization [17], [18] and achieve state-of-the-art (SOTA) with cm-level accuracy. In this article, we proposed a multirobot cooperative localization (MRCL) scheme which can realize robot localization simultaneously and relax the number of concurrently observable LEDs required for positioning to one.

MRCL technology is to locate a group of robots and improve the accuracy of their estimated positions by sharing information and using relative measurements, which benefits both the group and each individual robot in positioning accuracy, system robustness, and execution efficiency [19], [20]. As mobile robots become more affordable and reliable, the use of a group of robots becomes more and more feasible [21]. Many methods have been proposed to solve the problem of cooperative localization for multirobot system such as extended Kalman filter (EKF) [22]–[27], maximum likelihood

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estimation (MLE) [17], [28], [29], and maximum *a posteriori* (MAP) [18]. In [22], a cooperative localization algorithm based on the hybrid topology architecture under the framework of EKF is proposed to improve the usage efficiency of observations and accuracy of multiple mobile robot system. In [23], robots exchange their states with each other to obtain a global estimate by EKF. In [26], a method was proposed to periodically fuse the dead-reckoning results with the sound-based relative localization using EKF algorithm which can keep the real-time positioning error within 0.3 m, but it is worth mentioning that it requires at least one pose-known robot. In [27], a multirobot and ultra wideband cooperative localization approach with range-only measurement is proposed, and EKF is used to fuse the measured data.

Although MRCL technology has been intensely studied, there is little research in the literature that performs VLP technology in the presence of cooperative localization, especially the camera-based method. In cooperative localization based on VLP, robots not only receive information from the LED anchors but also exchange information with other robots. By obtaining the information from LED anchors and other robots within the communication range, collaborative localization can be carried out in a harsh environment with limited information to realize localization and improve coverage of positioning. In [17], a cooperative VLP system is proposed for the first time in the literature based on a generic system model consisting of LED transmitters at known locations and VLC units with multiple LEDs and PDs. In [18], an indoor VLP system based on cooperative localization is proposed based on MAP, which can provide cm-scale positioning accuracy. On the premise of relative measurement and communication between positioning terminal, these VLP-based cooperation systems in the literature only require double-LED anchors for each terminal, which reduces the LED deployment density to some extent.

In this article, we propose an MRCL system based on VLP and odometer (VO-MRCL). More specifically, under the condition that initial relative pose information of robots is given and the relative pose information between robots can be calculated by dead reckoning, the system can realize the positioning of each robot through only one detected LED information and the sharing of information between robots' communication. The proposed VO-MRCL system relaxes the required number of the observable LED anchors, that is to say, it can realize the localization of robots cooperatively in low-density LED deployment and improve the robustness of the VLP-based localization methods in harsh environment. With improved robustness under LED shortage, our scheme has a good usability for indoor robot localization. We highlight our novel contributions as follows:

1) An MRCL scheme based on VLP technology and odometer is proposed for robust VLP under LED shortage. We relax the assumption on the minimum number of simultaneously observable LEDs efficiently to one and improve the robustness of the VLP-based localization methods in harsh environment.
2) The scheme is evaluated in a real-world environment with a two-robot VO-MRCL system prototype with modulated LEDs. The prototyping system is verified with sufficient experiments and it can achieve an average accuracy of 4.31 cm.

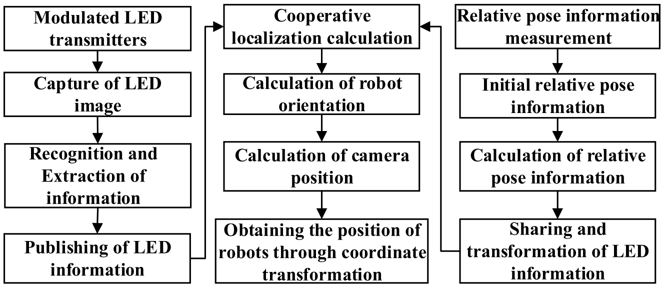

Fig. 1. Flowchart of the proposed VO-MRCL system.

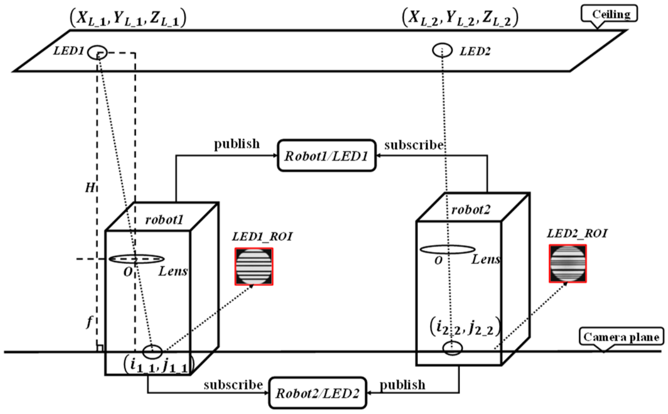

Fig. 2. Acquisition and sharing of LED information.

The rest of this article is organized as follows. In Section II, the proposed VO-MRCL system is introduced. The verification results are presented in Section III and the conclusions are drawn in Section IV.

## II. METHODOLOGY

### A. Overall Structure of the Proposed VO-MRCL System

The architecture of the proposed VO-MRCL system is shown in Fig. 1. The modulated LED lamps with VLC functions are used as transmitters of global positioning information. The images of LED were caught by a camera fixed vertically on robots. Each robot only needs one LED lamp, and then it recognizes the LED-ID and extracts the location information of LED through the mapping relationship. In addition, the information of LED obtained by each robot is not only used for itself but also be published and shared with other robots. Under the condition that the relative pose information among robots can be calculated by dead reckoning, the robots with known initial relative pose information can realize cooperative localization through information of one detected LED and information sharing.

### B. Principles of the Proposed VO-MRCL System

*1) Acquisition and Sharing of LED Information:* The acquisition and sharing of LED information is shown in Fig. 2.

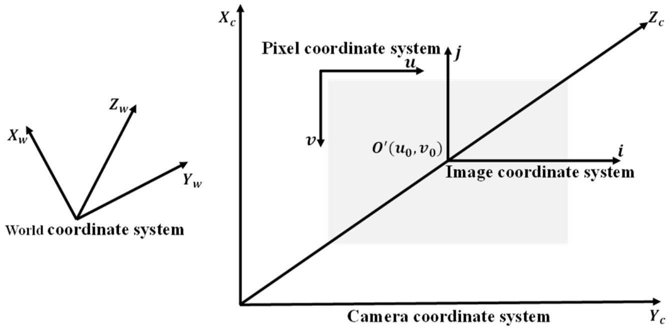

Fig. 3. Relationship between pixel coordinate system and image coordinate system.

The location information of LED $i$ in the global world coordinate system is already known and denoted as $(X_{L\_i}, Y_{L\_i}, Z_{L\_i})$. $(i_{t\_i}, j_{t\_i})$ is the centroid coordinate of LED $i$ in the image coordinate system of robot $t$, which can be obtained from the centroid coordinate$(u_{t_i}, v_{t_i})$ of the LED $i$ on the pixel plane. The relationship between pixel coordinate system and image coordinate system is shown in Fig. 3. Their relationship is shown as follows: 1 pixel $= du$ mm, and $du$ and $dv$ represent the unit conversion of the two coordinate systems. The conversion is shown in the following formula:

$$i = (u - u_0) \cdot du \tag{1}$$

$$j = (v - v_0) \cdot dv. \tag{2}$$

In the information acquisition process, the coordinate information of each LED is transmitted by modulating the LED light signals, and the robot uses the rolling shutter mechanism to capture the LED signal fringe images. The coordinate information of each LED uniquely maps to its light strip pattern. As shown in Fig. 2, to extract the regions of interest (ROIs) from camera perception and obtain the centroid pixel coordinates of LED projection, a LED-ROI extraction method is adopted. We first binarize the grayscale image by thresholding. We then subsample the LED images for low-cost calculation and use the LED template matching method to locate ROI in the image, and finally map ROI location back to the original image and extract ROI. After ROI extraction, coordinates' information $(X_{L\_i}, Y_{L\_i}, Z_{L\_i})$ stored in the LED signal fringe images are decoded and obtained based on the strip patterns of varying widths.

As shown in Fig. 2, the vertical distance from the lens center of image sensor to the fixed point of LED $H$ can be calculated

$$H = \frac{f}{r} \cdot R \tag{3}$$

where $f$ is the focal length of the image sensor which is a fixed parameter of the camera, $R$ is the radius of LED, and $r$ is the LED radius on the imaging plane which can be obtained through the projection of LED.

Therefore, the height of the center $Z_{t\_c}$ of the lens on robot $t$ can be obtained

$$Z_{t\_c} = Z_{L\_i} - H. \tag{4}$$

Assuming that $(x_{t\_i}, y_{t\_i}, z_{t\_i})$ is the coordinate of LED $i$ in the camera coordinate system of robot $t$, which can be obtained from the image coordinate $(i_{t\_i}, j_{t\_i})$ through the following formula:

$$\begin{cases} x_{t\_i} = -\dfrac{i_{t\_i}}{f} \cdot H \\ y_{t\_i} = -\dfrac{j_{t\_i}}{f} \cdot H \\ z_{t\_i} = H. \end{cases} \tag{5}$$

After the LED is recognized and the location information of LED is extracted, each robot publishes its LED information [$(X_{L\_i}, Y_{L\_i}, Z_{L\_i})$ in global frame and $(x_{t\_i}, y_{t\_i}, z_{t\_i})$ in camera frame] to a topic[1] in robot operating system[2] (ROS) with its own namespace.[3] Topic in ROS provides message transmission and reception among robots within the same network through which other robots can obtain the real-time sharing information of LED and transform it for their own use.

*2) Measurement of Relative Pose Information:* In the cooperative localization algorithm, we need to know the relative pose relationship among robots and the sharing of LED information to achieve positioning. Methods such as sound localization [26] that can measure relative pose information can be used in this part. In this article, we use odometer to calculate the relative pose information among robots under the precondition that initial relative pose information of robots is given. Therefore, the change of position of robot $t$ within time $T$ can be calculated by the following formula:

$$\begin{cases} x_t^T = x_t^{T-1} + v_t^{T-1} T \cos\theta_t^{T-1} \\ y_t^T = y_t^{T-1} + v_t^{T-1} T \sin\theta_t^{T-1} \\ z_t^T = Z_{t_c} \\ \theta_t^T = \theta_t^{T-1} + w_t^T T \end{cases} \tag{6}$$

where $v$ and $w$ denote the linear velocity and the angular velocity of the robot $t$, respectively, and $T$ presents the speed cycle.

The translation vector $T_t$ and quaternion $Q_t$ recorded by the odometer at each moment of robot $t$ can be denoted by the following formula:

$$T_t = \begin{pmatrix} x_t^T & y_t^T & z_t^T \end{pmatrix}^T \tag{7}$$

$$Q_t = \begin{bmatrix} 0 & 0 & \sin\left(\theta_t^T/2\right) & \cos\left(\theta_t^T/2\right) \end{bmatrix}. \tag{8}$$

*3) Transformation of LED Information:* An example of cooperative localization is described in the general situation, as shown in Fig. 4. Since the initial relative pose relationship of the robot is given, the translation vector and quaternion of robot 2 frame in robot 1 frame are represented by $T_{21}$ and $Q_{21}$, respectively. The translation vector $T_1$, $T_2$ and quaternion $Q_1$, $Q_2$ recorded by the odometer at each moment of robots can be obtained from (7) and (8), respectively. As shown in Fig. 4, through coordinate transformation, the robots can transfer the LED observation information in other robot's coordinate system to its own coordinate system. For example, robot 1 can obtain LED 2 information $(x_{1\_2}, y_{1\_2}, z_{1\_2})$ in its

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[1] http://wiki.ros.org/Topics

[2] https://www.ros.org/

[3] http://wiki.ros.org/Names

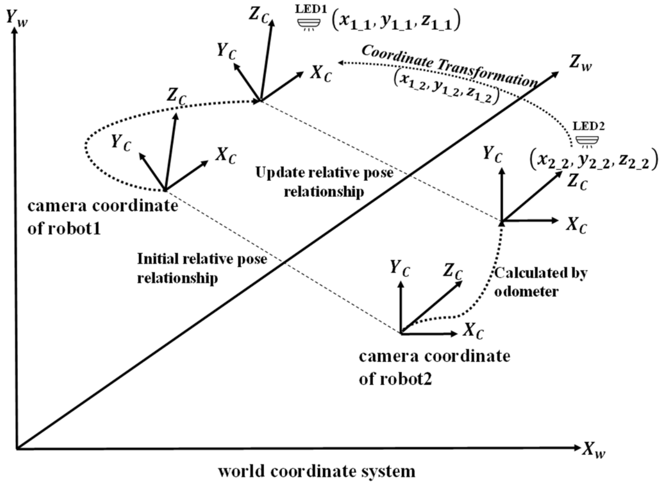

Fig. 4. Measurement of relative pose information and transformation of LED information.

own coordinate system shared from robot 2

$$\left[\begin{pmatrix}T_1\\0\end{pmatrix}+Q_1\begin{pmatrix}x_{1\_2}\\y_{1\_2}\\z_{1\_2}\\0\end{pmatrix}Q_1^{-1}\right] = Q_{21}\left[\begin{pmatrix}T_2\\0\end{pmatrix}+Q_2\begin{pmatrix}x_{2\_2}\\y_{2\_2}\\z_{2\_2}\\0\end{pmatrix}Q_2^{-1}\right]Q_{21}^{-1}+\begin{pmatrix}T_{21}\\0\end{pmatrix} \quad (9)$$

where $(x_{1\_2}, y_{1\_2}, z_{1\_2})$ denotes the coordinate of LED 2 in robot 1's camera coordinate system, and $(x_{2\_2}, y_{2\_2}, z_{2\_2})$ denotes the coordinate of LED 2 in robot 2's camera coordinate system.

As shown in Fig. 4, after the coordinate transformation, robot 1 can obtain the coordinate $(x_{1\_2}, y_{1\_2}, z_{1\_2})$ of LED 2 in its own camera coordinate system. In the same way, robot 2 can also obtain the coordinate $(x_{2\_1}, y_{2\_1}, z_{2\_1})$ of LED 1 in its own camera coordinate system.

*4) Cooperative Localization Algorithm:* After sharing and transformation of LED information, the yaw angle of the robot can be calculated based on the obtained LED information and the original detected LED information. As the global coordinates of LEDs are known, therefore, as shown in Fig. 5, assume that the angle between the vector of two LED centers and the $X_w$ axis of the world coordinate system is $\theta_t \in [-180°, 180°]$, and the yaw angle $\varphi_t \in [-180°, 180°]$ of the robot can be calculated according to the angle $r \in [0, 90°]$ between the vector of two LED centers in the camera coordinate system and the $X_C$ axis of the camera coordinate system. There are four kinds of circumstances as shown in Fig. 5, and $\theta_t$ and $r_t$ can be calculated by the following formula:

$$\theta_t = 2\text{atan}(Y_{L\_1} - Y_{L\_2}, X_{L\_1} - X_{L\_2}) \quad (10)$$

$$r_t = |\text{atan}(y_{t\_1} - y_{t\_2}, x_{t\_1} - x_{t\_2})|. \quad (11)$$

Under different circumstances, the yaw angle $\varphi_t$ can be obtained, as shown in Fig. 5.

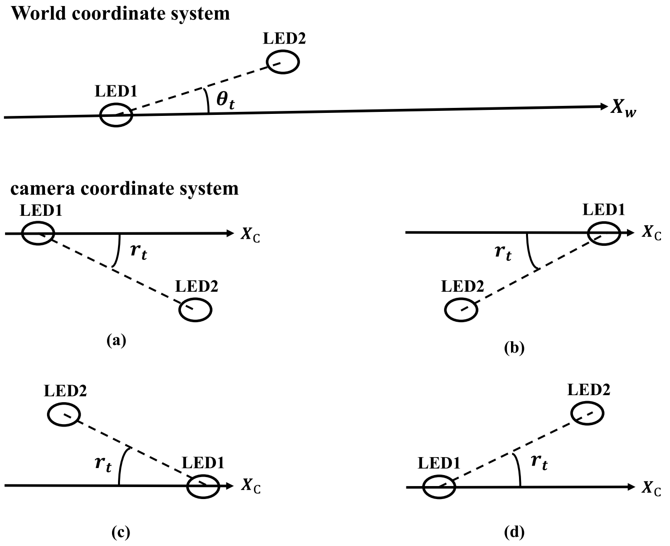

Fig. 5. Different situations of the yaw angle $\varphi_t$: (a) $\varphi_t = \theta_t + r_t$; (b) $\varphi_t = \theta_t + r_t + 90°$; (c) $\varphi_t = \theta_t + r_t - 180°$; (d) $\varphi_t = \theta_t + r_t - 90°$.

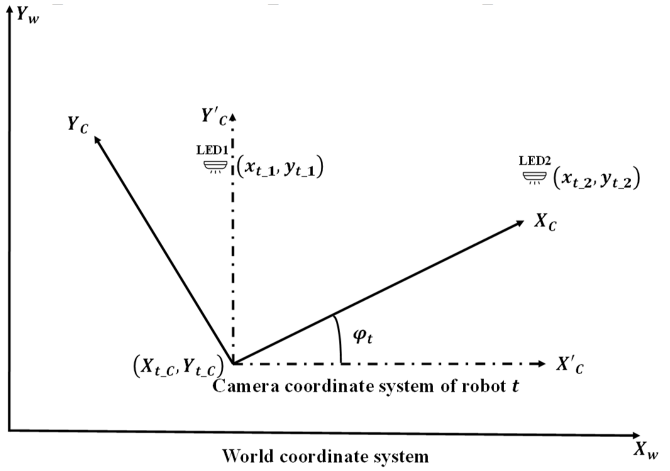

Fig. 6. Relationship between camera coordinate system of robot and world coordinate system.

As shown in Fig. 6, according to the LED information and yaw angle $\varphi_t$ of robot $t$, we can obtain the central coordinate $(X_{t\_c}, Y_{t\_c}, Z_{t\_c})$ of the camera of robot $t$ through the following formula:

$$\frac{X_{L\_1} + X_{L\_2}}{2} - X_{t\_c} = \frac{x_{t\_1} + x_{t\_2}}{2}\cos\varphi_t - \frac{y_{t\_1} + y_{t\_2}}{2}\sin\varphi_t \quad (12)$$

$$\frac{Y_{L\_1} + Y_{L\_2}}{2} - Y_{t_c} = \frac{y_{t_1} + y_{t_2}}{2}\cos\varphi_t + \frac{x_{t_1} + x_{t_2}}{2}\sin\varphi_t. \quad (13)$$

Therefore, the position of camera center $(X_{t\_c}, Y_{t\_c}, Z_{t\_c})$ of each robot can be calculated

$$\begin{bmatrix}X_{t\_c}\\Y_{t\_c}\\Z_{t\_c}\end{bmatrix} = \begin{bmatrix}\dfrac{X_{L\_1} + X_{L\_2}}{2}\\\dfrac{Y_{L\_1} + Y_{L\_2}}{2}\\0\end{bmatrix} - \begin{bmatrix}\cos\varphi_t & -\sin\varphi_t & 0\\\sin\varphi_t & \cos\varphi_t & 0\\0 & 0 & 1\end{bmatrix}$$

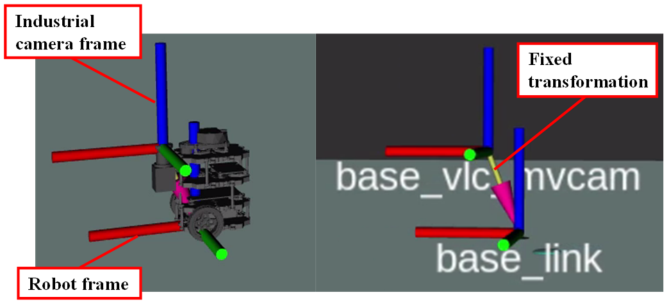

Fig. 7. Static transformation between robot and camera.

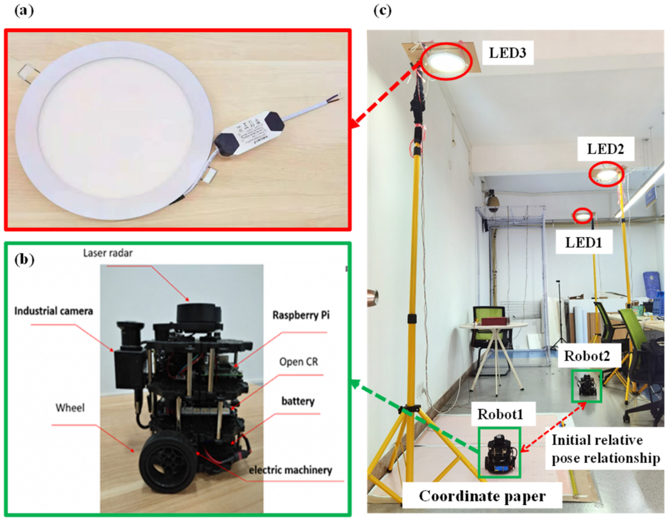

Fig. 8. Experimental setup of the proposed VO-MRCL system. (a) Our modulated LED. (b) TurtleBot3 Burger with industrial camera. (c) Experimental platform.

$$\times \begin{bmatrix} \dfrac{(x_{t_1} + x_{t_2})}{2} \\ \dfrac{(y_{t_1} + y_{t_2})}{2} \\ Z_{t_c} \end{bmatrix}. \tag{14}$$

Since the camera is fixed on the robot as shown in Fig. 7, the position of camera centers can be converted into the position $(X_t, Y_t, Z_t)$ of each robot by coordinate transformation through the following formula:

$$\begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix} = \begin{bmatrix} X_{t\_c} \\ Y_{t\_c} \\ Z_{t\_c} \end{bmatrix} + \begin{bmatrix} \cos\varphi_t & -\sin\varphi_t & 0 \\ \sin\varphi_t & \cos\varphi_t & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} \tag{15}$$

where $(\Delta x, \Delta y, \Delta z)$ is the offset of the center of the robot relative to the center of the lens.

## III. EXPERIMENT AND ANALYSIS

### A. System Setup

To verify the performance of the proposed VO-MRCL system, as shown in Fig. 8, an indoor environment is established with three modulated LEDs mounted on the yellow fixed pole. The evaluation is performed based on ROS which is a widely used open-source robotic framework in academia and industry. A two-robot VO-MRCL system is set up as an example and two-wheeled differential driving mobile robots Turtlebot3 Burger are used to conduct the experiment. Each robot is equipped with a MindVision UB-300 industrial camera with prior extrinsic calibration to catch LED information. To improve the speed of operation, we only conducted the acquisition of LED information and odometer on robots' processor Raspberry Pi 3 Model B that has weak processor performance for calculation, and the sharing and transformation of LED information and cooperative localization calculation are performed on the remote controller PC. More detailed parameters can be found in Table I.

TABLE I
PARAMETERS OF THE VO-MRCL SYSTEM

| **Camera Specifications** | |
|---|---|
| Model | MindVision® UB-300 |
| Pixel(H × V) | 2048 × 1536 |
| Time of Exposure | 0.02 ms |
| Type of Shutter Acquisition Mode | Electronic Rolling Shutter |
| **Turtlebot3 Robot Specifications** | |
| Module | Raspberry Pi 3 B |
| CPU | Quad Core 1.2 GHz Broadcom® BCM2837 |
| RAM | 1 GB |
| operating system | Ubuntu mate 18.04 |
| **Remote Controller Specifications** | |
| Module | Acer VN7-593G |
| CPU | Quad Core Intel® Core™ i7-7700HQ |
| operating system | Ubuntu 18.04 LTS |
| **LED Specifications** | |
| Coordinates of LED1(cm) | (500, 80, 270) |
| Coordinates of LED2(cm) | (300, 80, 270) |
| Coordinates of LED3(cm) | (0, 175, 270) |
| Diameter of each LED | 180mm |

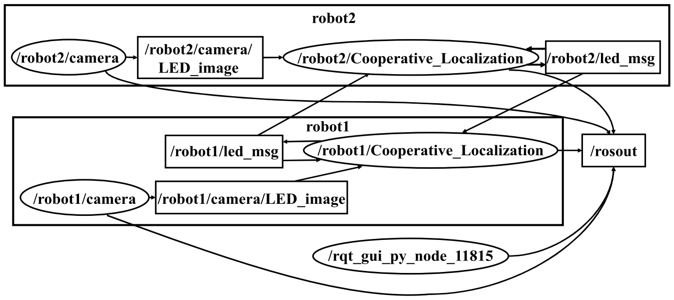

Fig. 9. Robot information sharing and communication graph of nodes and topics in different robot namespace in ROS of the two-robot VO-MRCL system prototype.

In the experiment, robots are placed randomly in the field with given initial relative pose information, and we set the translation vector $T_{21}$ to [300 −90 0 0] and the quaternion $Q_{21}$ to [0 0 0 1], as shown in Fig. 8. Robot 1 only detects LED 3, while robot 2 only detects LED 2. The robot information sharing and communication graph is shown in Fig. 9, and information of different robots is distinguished by different robot namespaces "robot1" and "robot2." Each robot captures the image of LEDs through camera and extracts LED-ROI, then the cooperative localization node can obtain the information

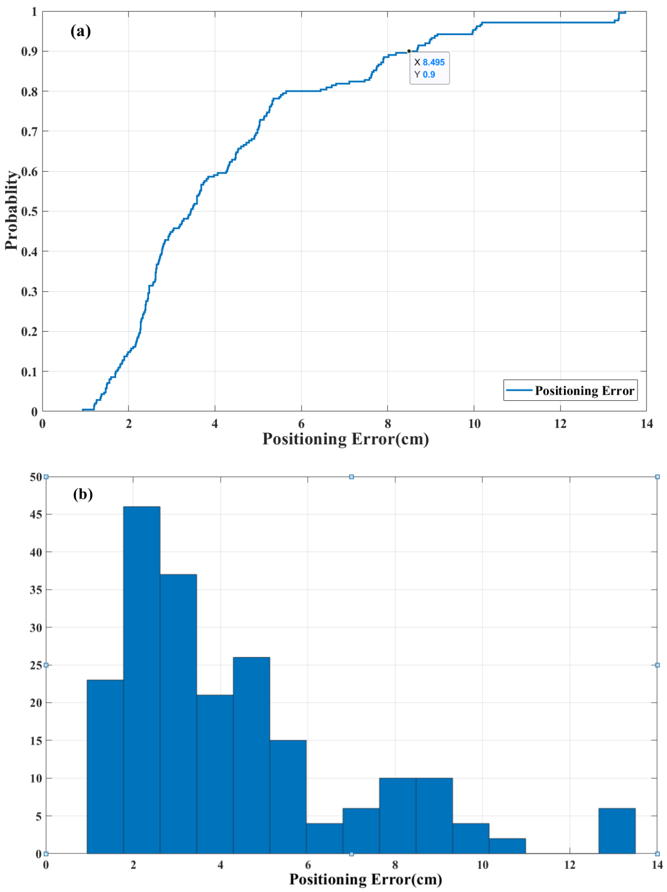

Fig. 10. Positioning errors of the proposed VO-MRCL system. (a) Cumulative distribution function (CDF) curves. (b) Frequency distribution histogram of positioning errors.

of location stored by the LED through LED-ID decoding, and finally it publishes its LED information to the topic "led_msg" in ROS for information sharing. Simultaneously, the relative pose information is calculated by the odometer. In the framework of multithreading and synchronization, robots can obtain the measurements of relative pose information and the real-time sharing information of LED; after transformation of LED information, robots can finally realize cooperative localization through the cooperative localization algorithm.

### B. VO-MRCL System Positioning Accuracy

To evaluate the position accuracy of the proposed VO-MRCL system, two series of experiment are carried out. The first series is to test the stationary positioning performance of the robots. The locations are randomly chosen in the experimental field for positioning accuracy verification of the VO-MRCL system. Robot 1 moves to different random locations on the coordinate paper and the accuracy of each point is verified, while robot 2 stays still to facilitate the experimental control. Thirty-five test locations are chosen in the experimental environment, and then the positioning error for each location is calculated by comparing the actual spatial position (manually measurement on the coordinate paper) and the estimated position (from ROS calculation). Each test point is measured six times, obtaining totally 210 stationary positioning results, and the average positioning error is 4.31 cm. As shown in Fig. 10, more than 90% positioning errors are less than 8.682 cm, and the confidence interval (95% confidence level) of the positioning error is [3.9341 4.6864] cm.

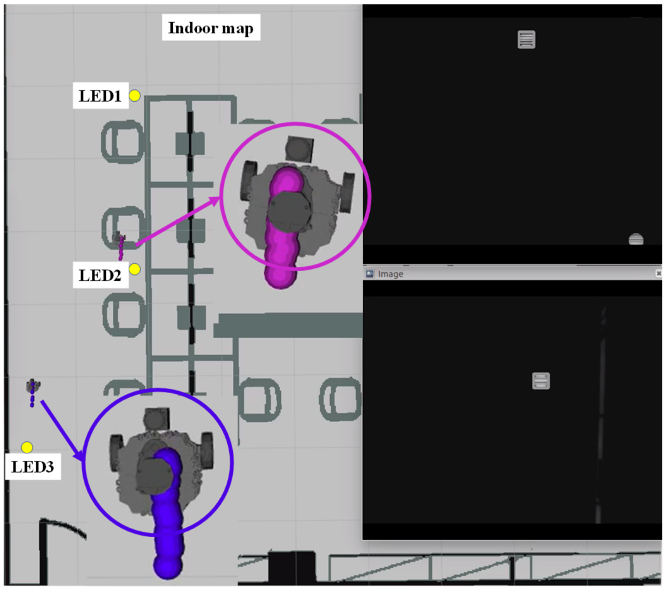

Fig. 11. Performance of the proposed VO-MRCL system with moving mobile robots.

The second series of experiment is to test the performance of the proposed VO-MRCL system with moving mobile robots. The robots were controlled to go straight and turning randomly to demonstrate the dynamic positioning effect of the VO-MRCL system with different speeds. As shown in Fig. 11, the positioning results of robots are represented by points in different colors. The algorithm results of robot 1 are plotted as blue dots and the results of robot 2 are plotted as purple dots. The points close to the robots are the results of the latest calculation of the cooperative positioning algorithm, and the other points are retained to better display the positioning results and the comparison of the robot's motion trajectory to show the effect of the VO-MRCL system. The demonstration video of our proposed VO-MRCL system is available in our website.[4]

### C. Discussion

In this section, we compare the performance of the proposed VO-MRCL system with the SOTA works in the VLP field in Table II. The average accuracy, required number of LEDs, and receiver type in the related experimental platform are displayed objectively in Table II. Compared with Refs. [3], [5], [16], and [18], our VO-MRCL system can relax the number of observable LEDs required for each positioning terminal. It is obvious that the accuracy (4.31 cm) of the proposed VO-MRCL system achieves SOTA. Moreover, in the proposed VO-MRCL system, multiple robots can realize

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[4] Our demo of the proposed VO-MRCL system is available at https://www.bilibili.com/video/BV1b54y1j7w4/

TABLE II
PERFORMANCE COMPARISON WITH THE SOTA METHODS

| Method | Average Accuracy (cm) | Require LEDs (at least) | Receiver Type |
|---|---|---|---|
| R.[16] | 14.0 | 3 | PD+IMU |
| R. [5] | 3.9 | 2 | Camera |
| R.[3] | 0.8 | 2 | Camera |
| R.[9] | 17.5 | 1* | Camera |
| R. [10] | 3.2 | 1* | Camera |
| R.[11] | 2.3 | 1* | Camera |
| R.[12] | 5.5 | 1 | Camera+IMU |
| R.[13] | 13.4 | 1 | Camera+PDR |
| R.[14] | 5.0 | 1 | Camera+IMU |
| R.[15] | 3.0 | 1 | Camera+IMU |
| R.[18] | 2-16$^{**}$ | 2 | PDs |
| ***Our VO-MRCL*** | 4.31 | 1 | Camera+Odometer |

“1*” means that the LED lamp with beacon (refer to Ref. [9], [10], [11])

“2-16$^{**}$”means that the positioning accuracy errors decrease from 16cm to 2cm as the signal-to-noise ratio increases from 20dB to 40dB (refer to Ref. [18])

localization simultaneously through one detected LED for each robot, relative measurement, and exchanging information. Admittedly, we would not take the cumulative error of the odometer into consideration, which might affect the positioning accuracy over time. We will try to analyze this and explore an efficient method for error calibration of odometer based on VLP observation or a tightly coupled fusion method. We credit our contribution mainly to the MRCL scheme based on VLP technology and odometer, which relaxes the assumption on the minimum number of simultaneously observable LEDs efficiently to one. Moreover, the delivered accuracy is basically enough for many indoor robot applications.

## IV. CONCLUSION

In this article, we propose a multirobot cooperative system based on VLP and odometer. The system can realize the positioning of robots with one detected LED and the exchange of information among robots, which reduces the deployment density of LED lamps, and can improve the robustness of VLP-based robot positioning methods. Through cooperation among robots, the system can work even in harsh environment, and a two-robot system is proposed as an example specifically. The experiments of cooperative localization system using two mobile robots show that the multirobot cooperative VO-MRCL system can realize cooperative localization and provide cm-scale positioning accuracy. In the future, we will continue to further explore and optimize the collaborative localization algorithm.

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