Indoor Positioning Method Based on Infrared Vision and UWB Fusion

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Abstract. Ultra-wideband (UWB) has broad application prospects in the field of indoor localization. In order to make up for the shortcomings of ultra-wideband that is easily affected by the environment, a positioning method based on the fusion of infrared vision and ultra-wideband is proposed. Infrared vision assists locating by identifying artificial landmarks attached to the ceiling. UWB uses an adaptive weight positioning algorithm to improve the positioning accuracy of the edge of the UWB positioning coverage area. Extended Kalman filter (EKF) is used to fuse the real-time location information of the two. Finally, the intelligent mobile vehicle-mounted platform is used to collect infrared images and UWB ranging information in the indoor environment to verify the fusion method. Experimental results show that the fusion positioning method is better than any positioning method, has the advantages of low cost, real-time performance, and robustness, and can achieve centimeter-level positioning accuracy.

1. Introduction
In mobile robot applications, one of the most basic functions and challenges is to locate accurately, reliably and efficiently. In recent years, the positioning function of indoor service robots has been demanded for higher accuracy and robustness in the transportation and service fields. There are many ways to obtain the position information of the robot, such as finger-printing positioning method, proximity detection method and representative based on time of arrival (TOA), time difference of arrival (TDOA), angle of arrival (AOA) and received signal strength index (RSSI) Distance estimation methods. Based on these positioning methods, a variety of indoor positioning technologies have been derived. The mainstream ones include visual positioning, ultrasonic, WLAN, RFID, UWB and Bluetooth, etc.

Among the existing solutions, visual positioning has attracted more and more attention due to its advantages such as no cumulative error, high accuracy and low cost. Reference [1] proposed a positioning method based on artificial landmarks on the ceiling, designed a landmark pattern combining letters and colors, recognized the landmarks through color image segmentation and contour rectangle matching methods, and then calculated the positioning information through image rotation and translation transformation. Reference [2] designed an artificial landmark with black and white concentric circles, determined the threshold by counting the pixel values, and binarized the image to extract the ROI area and identify the landmark information. Reference [3] uses a two-dimensional code as an artificial landmark, calls the tool library to identify and scan the two-dimensional code, and
obtains the global position information of the two-dimensional code. Finally, the pixel coordinates of the image center are converted into the actual coordinates of the camera through geometric transformation. Reference [4] proposed a positioning method based on infrared landmarks, referring to the design of a two-dimensional code, using three reflective markers forming an equilateral right triangle to identify the heading angle. The external parameters of the camera were calculated by P3P algorithm and the location of the camera was deduced accordingly.

In indoor positioning, UWB technology is widely used. It has the characteristics of short pulse interval, high time resolution and strong obstacle penetration ability. It can obtain centimeter-level positioning accuracy in a line-of-sight environment, and is suitable for high-precision positioning in indoor environments[5][6]. Reference [7] proposes an improved two-way ranging method, which reduces the measurement error of flight time through three signal transmissions and realizes real-time location tracking in a smart supermarket. Reference [8] also proposed a twice triangle centroid positioning algorithm based on the improvement of the two-way ranging method. By increasing the number of anchors, the influence of ranging errors is reduced, and the accuracy and stability of positioning are improved.

Both visual positioning technology and UWB positioning technology are based on the data signal of a single sensor to achieve positioning, and are susceptible to interference from the surrounding environment. Based on the above, the fusion of multiple sensors can make the robot more comprehensively perceive environmental information and make up for the shortcomings of a single sensor [9-11]. Reference [12] proposes an indoor human body positioning method based on IMU and infrared sensor network. IMU is used to collect human motion data, derive the human motion model through the PDR algorithm, and then use the observation data of the infrared sensor network to assist in reducing Intermediate error in the process of positioning and tracking. Reference [13] uses IMU, UWB and vision sensor data to fuse to achieve positioning. In the UWB ranging process, the vision module is used to detect the circle label on the anchor to estimate the distance, and help reduce the UWB ranging error. Reference [14] also uses the above three sensors, but the vision module uses the ZED tracking camera to implement the stereo vision tracking algorithm. In the positioning technology of multi-sensor data fusion, the utilization rate of IMU equipment is extremely high. It can obtain information such as the acceleration and angular velocity of the robot, and can stably provide reliable data even in complex environments, and is often used to assist in improving the positioning accuracy. However, IMU still has disadvantages such as high price and cumulative error [15].

After comprehensively considering the advantages and challenges of visual positioning technology and UWB positioning technology, this paper proposes a low-cost, high-precision and robust indoor positioning method. It improves the positioning accuracy by improving the UWB positioning algorithm and uses artificial infrared reflective properties. The landmarks are assisted by visual positioning at the same time, using a combination of relative positioning and absolute positioning to establish an observation model. Finally, EKF is used to fuse the results of the two positioning methods to achieve an accurate and stable estimation of the robot's position and heading angle.

2. Infrared Vision Positioning

2.1. Label and image processing
The infrared tag is attached to the ceiling, and the line-of-sight occlusion rate is effectively reduced. It consists of a 4x4 dot matrix arrangement, with three fixed points on the periphery as the basis for direction determination, noted as LeftTop, RightTop and LeftBottom, and the remaining points at different positions to identify different tags in different arrangements. After the on-board infrared narrowband camera captures the image containing the tag, as shown in Figure 1, the following image processing and calculation are performed:

- The original image is grayed out and binarized to filter out the effects of interferences that do not have infrared reflective properties.
Using the Canny edge detection algorithm to obtain the edges and contours of all highlighted regions to obtain the outer rectangle of all contours.

- The external rectangles belonging to the labeled dot matrix are filtered according to the threshold value, and all external rectangles are clustered using the KNN algorithm idea.

- The rectangles of the same kind form a label, using the longest diagonal and vertical nature to determine three fixed points, take the midpoint of the two points of the diagonal and LeftTop point line, calculate the clockwise direction of the line to the angle between the two points and LeftTop point line, the angle of the smaller identified as LeftBottom, and finally calculate the angle between the vector with LeftBottom point as the starting point and LeftTop point as the end point and the y-axis of the pixel coordinate system to obtain the rotation angle.

- After affine transformation, except for the 3 fixed points, they are detected sequentially from left to right and from top to bottom, and if a point exists at that position, it is recorded as 1, otherwise it is recorded as 0. According to the order from low to high, a string of binary codes is formed as the tag number, which is used to distinguish different tags, the ID of tag 1 is 10010101.

![Figure 1. Label recognition process.](image)

**2.2. Absolute position calculation**

The ceiling is perpendicular to the optical axis of the on-board camera, and the labels in the image only undergo linear transformation and translation with almost no distortion. According to the transformation relationship between the world coordinate system, the image coordinate system and the pixel coordinate system, the absolute position pose of the camera can be deduced by equation (1):

\[
\begin{align*}
x_R &= \mu_x |OL| \sin \theta + x_Li \\
y_R &= \mu_y |OL| \cos \theta + y_Li
\end{align*}
\]

(1)

where \( \theta \) is the label rotation angle, \( \mu_x \) and \( \mu_y \) is the ratio of the physical size of the label to the pixel size, \( |OL| \) is the pixel Euclidean distance between the center of the image and the label LeftTop point, and \( x_Li \) and \( y_Li \) is the absolute position coordinate of the label with number i.

**3. UWB Positioning**

**3.1. Distance measurement algorithm**

Among the TOA-based UWB positioning methods, Asymmetric Double-sided Two-way ranging (ADS-TWR) does not require clock calibration and synchronization between devices, nor does it require the same device reply time. This is related to the antenna delay, which can be measured several times in advance at a fixed distance to measure the antenna delay error and automatically eliminate the error when positioning, effectively improving the positioning accuracy of the tag. The communication flow between the tag and the base station is shown in Figure 2. The tag first sends a Poll message, the base station receives it and replies with a Resp message, the tag receives it and then sends a Final
message. This is the end of a round of ranging communication containing three messages transmitted, and the time of flight is obtained:

\[ T_{\text{prop}} = \frac{T_{\text{round1}} \times T_{\text{round2}} - T_{\text{reply1}} \times T_{\text{reply2}}}{T_{\text{round1}} + T_{\text{round2}} + T_{\text{reply1}} + T_{\text{reply2}}} \]  \hspace{1cm} (2)

Figure 2. Label recognition process.

3.2. Positioning algorithm with adaptive weights

The principle of UWB two-dimensional positioning is to find the intersection of three circles with the base station as the center and the measured distance value as the radius, and the tag coordinates can be found by using the trilateral measurement algorithm. The coordinates of base stations 0, 1, and 2 are known to be \((x_0, y_0)\), \((x_1, y_1)\), and \((x_2, y_2)\), the measured distance from each base station to the tag is noted as \(r_0\), \(r_1\), and \(r_2\), then:

\[
\begin{align*}
    r_0 &= \sqrt{(x_0 - x)^2 + (y_0 - y)^2} \\
    r_1 &= \sqrt{(x_1 - x)^2 + (y_1 - y)^2} \\
    r_2 &= \sqrt{(x_2 - x)^2 + (y_2 - y)^2}
\end{align*}
\]  \hspace{1cm} (3)

However, in practical applications, there is often more than one intersection point because of interference from noise and obstacles, etc. The most common solution is the triangular center-of-mass method, and this practice of averaging introduces large deviations. Therefore, adaptive weights are proposed, and if there is an anomaly that is too far from the mean, the weight of the anomalous intersection should be reduced, and the specific solution steps are as follows:

- Get the coordinates of the intersection points \(Q_0(x_0, y_0)\), \(Q_1(x_1, y_1)\), and \(Q_2(x_2, y_2)\), and calculate centroid coordinate \((\bar{x}, \bar{y})\);
- Calculate the deviation of each intersection point, and record as \(D_i\):
  \[ D_i = D(Q, M) = \|Q - M\| \]  \hspace{1cm} (4)
- Calculate the weights of the intersection points, denoted as \(W_i\):
  \[ W_i = \frac{\prod_{j=1, j \neq i} D_j}{\sum_{j=1, j \neq i} \sum_{k=0} D_jD_k} \]  \hspace{1cm} (5)
- Calculate the weighted final positioning result, denoted as \(R(x, y)\):
  \[ R(x, y) = \sum_{i=0} W_iQ_i \]  \hspace{1cm} (6)
4. Fusion Strategy

4.1. Data Fusion Structure
In this paper, the parallel architecture is used for multi-sensor data fusion. EKF is used to realize the fusion. The input is the measured value of UWB and infrared vision positioning estimation at the same time and the noise covariance of the sensor, among which the measured value of the former is regarded as the predicted value of the system, and the measured value of the latter is regarded as the measurement value of the system. The output optimal fusion estimation is calculated by the filter, which is the optimal positioning result.

4.2. Fusion Algorithm
EKF is an extended form of the standard Kalman filter in the case of nonlinearity. which is suitable for multi-sensor data fusion positioning systems. The description equation of nonlinear dynamic system in this paper is as follows:

\[ X_k = F(X_{k-1}) + \mathbf{e}_{k-1} \]  \hspace{1cm} (7)
\[ Z_k = H(X_k) + \mathbf{v}_k \]  \hspace{1cm} (8)

where \( \mathbf{e}_{k-1} \) is the system process noise subject to Gaussian distribution. \( \mathbf{v}_k \) is the measurement process noise subject to Gaussian distribution, \( X_{k-1} = \begin{bmatrix} x_{k-1}^u \\ y_{k-1}^u \end{bmatrix}, \) \( x_{k-1}^u \) and \( y_{k-1}^u \) is the observation value of UWB positioning module, \( Z_k \) is determined by the observation value of infrared vision positioning module.

The equation of EKF prediction process is:

\[ \hat{X}_k^- = F(\hat{X}_{k-1}) \]  \hspace{1cm} (9)
\[ P_k^- = A P_{k-1}^- \mathbf{A}^T + Q_{k-1} \]  \hspace{1cm} (10)

where the transformation matrix \( \mathbf{A} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \), \( Q_{k-1} \) is the noise covariance of the system process, which is input by the UWB positioning module, combined with the noise situation of the UWB equipment in the current environment and the positioning error data of the module.

Then calculate the Kalman gain matrix \( K_k \) at time k:

\[ K_k = \frac{P_k^- H^T}{H P_k^- H^T + R_{k-1}} \]  \hspace{1cm} (11)

where, \( R_{k-1} \) is the noise covariance of the measurement process, which is input by the infrared vision positioning module, and is also obtained by combining the noise situation of the visual equipment and the positioning error data of the module in the current environment.

At the same time, update the posterior state \( \hat{X}_k \) and the posterior covariance \( P_k \) at time k:

\[ \hat{X}_k = \hat{X}_k^- + K_k (Z_k - H(\hat{X}_k^-)) \]  \hspace{1cm} (12)
\[ P_k = (I - K_k H) P_k^- \]  \hspace{1cm} (13)

Finally, \( P_k \) at time k is brought into (10) for the system covariance calculation at the next time, and the posterior state \( \hat{X}_k \) is output as the optimal fusion result at the current time as the final location estimation result.
5. Experiment and Result Analysis

5.1. Experimental Platform Construction
The experiment uses a cart of ROS master control system as a carrier, equipped with a camera and UWB device, as shown in Figure 3. The camera is an infrared narrowband 940nm camera with a frame rate of 30fps and a resolution of 1280x1090 pixels. The UWB localization communication module is DWM1000, and the range calculation is done on the chip STM32. Image processing, visual positioning calculation and UWB positioning calculation are all done in the main control board of the cart, configured with Raspberry Pi 4B and Nvidia Jetson Nano.

Figure 3. Experimental equipments.

5.2. Experimental Analysis of Adaptive Weight UWB Positioning
In order to verify that the adaptive weight UWB positioning algorithm has better positioning accuracy than the centroid positioning algorithm, the tag is placed inside and outside the area enclosed by the three anchors for positioning measurement. As shown in Figure 4, the areas covered by the base stations are selected. A total of 20 reference points were collected for positioning data, including 5 points at the boundary of the area, and 8 points outside the area. It turns out that there is not much difference in the positioning accuracy of the two in the area, but the positioning accuracy of the UWB positioning algorithm with adaptive weight is significantly higher than that of the centroid positioning algorithm at the boundary and outside of the area.

The results show that the average error of the x-axis and y-axis of the centroid positioning algorithm is 26.1cm, 16.1cm, while the average error of the x-axis and y-axis of the adaptive weight UWB positioning algorithm is 12.8 cm, 7.0 cm, which means that the positioning accuracy of x-axis and y-axis is improved by 51% and 57% respectively. In addition, the average Euclidean distance error of the centroid localization algorithm is 30.9 cm, and the average Euclidean distance error of the adaptive weight UWB localization algorithm is 14.7 cm. Compared with the twice triangle centroid localization algorithm [8], the average error of the proposed method is improved by 15.3 cm, that is, the total positioning accuracy is improved by 52%.

Figure 4. Adaptive weight UWB localization results.
5.3. Comparative Experiment Analysis

In order to evaluate the positioning accuracy of the fusion positioning method proposed in this paper, 100 static sampling points are collected. The positioning errors of the three positioning methods on x-axis and y-axis are shown in Figure 5.

![Figure 5. Sample point error results.](image)

Table 1. Accuracy comparison of three positioning methods.

| Method    | x-axis error/cm | y-axis error/cm | Heading angle/° |
|-----------|-----------------|-----------------|-----------------|
|           | mean | max | variance | mean | max | variance |
| vision    | 2.6   | 6.7 | 4.6      | 1.6  | 5.1 | 4.1      |
| UWB       | 10.6  | 13.6| 2.7      | 10.3 | 15.2| 4.0      |
| fusion    | 1.9   | 5.4 | 2.2      | 1.4  | 3.5 | 2.8      |

In order to verify the real-time and robustness of the fusion localization method proposed in this paper, the handle remote control trolley was driven around a fixed path and the localization data were obtained every 100ms, and the measured driving trajectories of different methods were compared with the real trajectories as shown in Figure 6. Analyzing the experimental results, it is found that the positioning results obtained by using the fusion positioning method are better than those obtained by using any one of the single sensors. After the fusion algorithm, the positioning result not only has improved accuracy, but also has no great deviation in the whole driving trajectory including the inflection point, and the measured trajectory is basically indistinguishable from the real one.

![Figure 6. Dynamic positioning track chart.](image)

6. Conclusion

In this paper, we propose a fusion indoor positioning method based on infrared vision and UWB. On the basis of optimizing UWB positioning algorithm, using the infrared vision positioning of artificial landmarks based on the 4x4 dot matrix pattern on the ceiling as an aid, and using the EKF algorithm to optimize the fusion result data of the two positioning methods, compared with the positioning method of a single sensor, the method proposed in this paper has the advantages of faster speed, high accuracy and robustness. Compared with other common UWB and IMU fusion positioning methods, in the method proposed in this paper, the infrared vision positioning method is used as an auxiliary to improve the UWB positioning accuracy, which has the characteristics of low cost and high accuracy, and has certain practical application value.
Acknowledgments
This work is supported by National Natural Science Foundation of China(U20A20161).

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