Chapter 2
Human Tracking System Based on PIR Sensor Network and Video

Ji Xiong, Fang-Min Li and Jing-Yuan Zhang

Abstract To detect and locate the human target motion precisely, this paper intends to present a tracking algorithm based on pyroelectric sensor network and video analysis technologies. According to the advantages of pyroelectric sensor network system and video system, this paper uses weighted least squares to fuse the data which is collected by multiple heterogeneous sensor nodes to realize human target real-time tracking. Moreover, the data can also be collected by pyroelectric sensor network system and video cameras. Through simulation, the error of tracking results is analyzed. The results show that the method using homogeneous and heterogeneous sensors to fuse the measured vector obtain better human target real-time tracking effect.

Keywords Human tracking · Pyroelectric infrared sensors network · Video · The weighted least squares method

2.1 Introduction

Pyroelectric infrared sensor, a noncontact form used to detect the infrared radiation changes in the environment, has a relative sensitivity to the human movement. In addition, it has other advantages such as wide application range, strong concealment performance and little influence of the ambient light. Therefore, the technology using PIR (Pyroelectric Infrared) to locate and track targets has received special attention. In relevant literature [1–4], Qi Hao and other researchers have made an in-depth study in this field and have utilized PIR to realize human targets real-time tracking. They designed the PIR nodes to detect human movement by using PIR sensors.

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According to the relative angle changes of human body movement and based on the space-time conversion model, the PIR nodes completed the human target tracking and recognition. They also used the fusion algorithm based on kalman and particle filter algorithm to fuse the human data which was collected by the four fixed PIR nodes and have conducted an experiment in a real environment on human tracking. Because of the limited accuracy of pyroelectric sensor, the tracking effect is relatively poor in multibody tracking.

In literature [5–7], these papers explained that the tracking and recognition based on video were relatively mature and in multibody tracking, and the effect was quite good. However, the tracking based on video information requires a higher ability for data processing and at the same time, the amount of collected tracking data is relatively big. In the process of using wireless network to transfer the tracking information, because the wireless network bandwidth is relatively limited, the wireless network cannot play an effective real-time video tracking function in transferring the tracking information. Therefore, using pyroelectric sensors to mix with the video system for surveillance become the focus of our research. The paper discusses the sensors' advantages and disadvantages, respectively, in the system of heterogeneous sensor network, which has both the active sensors (camera with a PTZ system) and the passive sensors (pyroelectric sensor node). The pyroelectric sensor nodes can measure the azimuthal angle of the target, but cannot measure the target distance, while the video camera can. Two kinds of sensors to get complementary measurements at the same time, and merging forms a system which is beneficial for human tracking [8, 9].

The literature [10] used HMM algorithm to estimate the target location and single human target tracking. HMM tracking method, an advanced solution method, solves the target trajectory through iteration. However, this approach must plan the tracking area first and get the prior distribution for the human body target trajectory tracking. In order to obtain more accurate position estimation, the method needs more iterations and a large amount of calculation. According to the respective advantages of heterogeneous sensors, our study makes use of the redundant information from the sensors to measure data and complement the incomplete measurement to a complete one. Then the target position is calculated by using extended weighted least squares method. Meanwhile, in order to facilitate the discussion, we assume that the observation noise is independent of Gauss noise, and in the position measurement, there would be at least two sources of measurement from the pyroelectric sensors. What is more, using the video camera as one kind of sensor in the heterogeneous sensor networks will play an important role in the target identification and multihuman target tracking.

2.2 Description of the Problem and the Overall Framework

In the process of real-time target tracking, high-end video cameras are used in real-time target tracking. While in this case, the data backup and network transmission requires better bandwidth, especially in the wireless environment. Therefore, it is

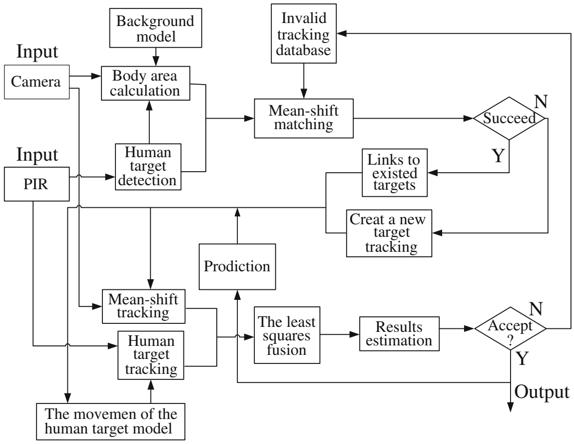

Fig. 2.1 Overall functional framework

difficult to achieve good results. At the same time, the high-end video cameras will not play their proper function when they are in the relatively hostile environments. Some of the researchers have proposed that according to the characteristics of the released red infrared from human body, the technology of pyroelectric sensor can be used for human target tracking and recognition. But the tracking accuracy is not very satisfactory, and it needs to optimize the tracking environment. It cannot achieve the desired effect in the actual environment. In multihuman target tracking, the error rate is higher. Based on the previous studies, this paper has explored a new method to add a camera to the pyroelectric sensors network which can not only make the pyroelectric network systems and camera systems work individually when tracking human body, but also can fuse the measurement obtained by the two different systems to track the human target. This method can overcome the problems which exist in the previous studies and has the potential for wide application.

In order to overcome the uncertainty of target state and limitations of the individuals or single type of sensor measurement, the paper proposes a way which can improve the effect of the sensors network system and accurately describe the measured target by fusing the data that are obtained by a variety of sensors. The paper [11, 12] used the least squares method to fuse and estimate the data which are measured by the same kind of sensors. In the data acquisition system, different kinds of sensors information fusion are important. By using the data measured by multiple heterogeneous sensors, the aim of monitoring various parameters and tracking multiple targets has been achieved.

In this paper, the fusion method based on the principle of least squares is simple in calculation. It can objectively reflect the reliability of each sensor. In data processing, it does not need to know a priori information about the data, and the fusion result has high accuracy. As Fig. 2.1 shows, the functional framework which is composed by the pyroelectric network and video system and it expounds the general concept.

2.2.1 Heterogeneous Sensor Data Fusion Method

We used the weighted least squares method to get the estimate vector $\widehat{\mathrm{x}}$ which is computed from the measurement vector y_i. The criterion of weighted least squares estimation is to make the sum of weighted squared error as shown in the following formula to reach its minimum.

$$J_w(\widehat{\mathrm{x}}) = (y_i - H_i\widehat{\mathrm{x}})^T W(y_i - H_i\widehat{\mathrm{x}}) \tag{2.1}$$

In formula (2.1), W is a positive diagonal weighting matrix, and $W = \mathrm{diag}(w_1, w_2, \ldots, w_i, \ldots, w_n)$. W is the weight coefficient matrix, and $w_i \in R^{n_i \times n_i}$.

Theorem 1. *The ith sensor and the jth sensor consist of rangefinders matrix, which are $H_i \in R^{n_i \times m}$ and $H_j \in R_{n_j \times m}$ $(H_i \neq H_j)$ the random vector $\widehat{x}$ is the least squares estimation.*

$$\widehat{x} = \left[\sum_{i=1}^{n} H_i^T V_i^{-1} H_i\right]^{-1} \sum_{i=1}^{n} H_i^T V_i^{-1} y_i \qquad i = 1, 2, \ldots, n \tag{2.2}$$

In formula (2.2), V_i is error variance matrix of the ith sensor, to prove the theorem 1 as follows:

Proof: In order to reduce the weighted error sum of squares to minimum, we assume that $\frac{\partial J_w}{\partial \mathrm{X}} = 0$, so we can get formula (2.3)

$$-H_i^T(W + W^T)^T W(y_i - H_i\widehat{\mathrm{x}}) = -H_i^T(W + W^T)y_i + H_i^T(W + W^T)H_i\widehat{\mathrm{x}} = 0 \tag{2.3}$$

The nature of the diagonal matrix shows

$$W = W^T, \quad \widehat{\mathrm{x}} = \left[\sum_{i=1}^{n} H_i^T W_i H_i\right]^{-1} \sum_{i=1}^{n} H_i^T W_i y_i \tag{2.4}$$

Using the principle of least squares weighted fusion algorithm is also an unbiased estimation algorithm in the heterogeneous sensors, so we can get the estimated variance matrix R of $\widehat{\mathrm{x}}$.

$$R = E[e(\widehat{\mathrm{x}})e^T(\widehat{\mathrm{x}})] = E[(x - \widehat{\mathrm{x}}^2)] = E\left\{\left[x - \left(\sum_{i=1}^{n} H_i^T w_i H_i\right)^{-1} \sum_{i=1}^{n} H_i^T w_i y_i\right]^2\right\}$$

$$= E\left\{\sum_{i=1}^{n}\left[\left(\frac{w^i}{\sum\limits_{i=1}^{n}} w_i\right)^2 H_i^T (H_i x - y_i)(H_i x - y_i)^T H_i\right]\right.$$
$$\left. + \sum_{i=1}^{n}\sum_{j=1, j\neq i}^{n}\left[\frac{w_i w_j}{\left(\sum\limits_{i=1}^{n} w_i\right)^2} H_i^T (H_i x - y_i)(H_j x - y_j)^T H_i\right]\right\} \quad (2.5)$$

Because V_i and V_j are independent of each other, therefore

$$E[(H_i x - y_i)(H_j x - y_j)^T] = 0 \quad i \neq j \quad (2.6)$$

$$R = E[e(\widehat{x})e^T(\widehat{x})] = E\sum_{i=1}^{n}\left[\left(\frac{w_i}{\sum\limits_{i=1}^{n}}\right)^2 H_i^T (H_i x - y_i)(H_i x - y_i)^T H_i\right] \quad (2.7)$$

$$R = \sum_{i=1}^{n}\left[\left(\frac{w_i}{\sum_{i=1}^{n} w_i}\right)^2 H_i^T V_i H_i\right] \quad (2.8)$$

Through finding the minimum error, taking the partial derivative of W_i, and obtaining $\partial R/\partial w_i = 0$, we can get W_i as follow:

$$w_i = H_i V_i^{-1} H_i^T, \quad i = 1, 2, \ldots, n \quad (2.9)$$

And we can get R and $\widehat{x}$

$$R = \left[\sum_{i=1}^{n} H_i^T V_i^{-1} H_i\right]^{-1} \quad (2.10)$$

$$\widehat{x} = \left[\sum_{i=1}^{n} H_i^T V_i^{-1} H_i\right]^{-1} \cdot \sum_{i=1}^{n} H_i^T V_i^{-1} y_i = R \cdot \sum_{i=1}^{n} H_i^T V_i^{-1} y_i \quad (2.11)$$

2.3 Heterogeneous Sensors Hybrid Tracking Model Design

This paper has proposed a mixed tracking model of heterogeneous sensors, which comprises a camera system and a pyroelectric infrared sensor system. According to the physical properties of pyroelectric infrared sensors, the direction angle of

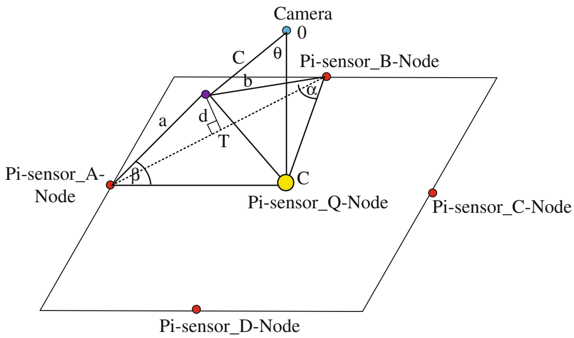

Fig. 2.2 Design for mixed tracking model

human body in the area of target tracking can be obtained. When the camera gets the human information, it can conduct the simple image processing. Thus we can get the relative distance between the target and camera. As the Fig. 2.2 shows, the tracking area is composed of five pyroelectric infrared sensor nodes and a PTZ camera. The heterogeneous pyroelectric sensor nodes system is comprised of nodes A, B, and Q. As Fig. 2.2 shows, it can get the primary positioning and tracking of human target. Meanwhile, we can transfer the location data of human to camera [13], so that we can make use of the heterogeneous tracking mode which consists of a camera and nodes A and B for tracking and recognition.

2.3.1 Homogeneous Sensor Positioning Method

Pyroelectric sensor location system belongs to the homogeneity sensor location system. The AOA location model that the system uses is simple and has strong real-time performance. We assume that the position of pyroelectric sensor node is (x_i, y_i) and that of the human target position is (x, y). Each value of θ_i measured by using AOA mode is opposite. Therefore, the expression is as follows:

$$\tan\theta_i = \frac{y - y_i}{x - x_i}, \quad i = 1, 2, \ldots, m \tag{2.12}$$

And formula (2.12) can be converted to: $\tan(\theta_i) \times x - y = \tan(\theta_i) \times x_i - y_i$, $i = 1, 2, \ldots, m$.

Error equation:

$$\psi = H - Y \times x \tag{2.13}$$

$$H=\begin{bmatrix}\tan\theta_1 & -1\\ \tan\theta_2 & -1\\ \vdots & \vdots\\ \tan\theta_m & -1\end{bmatrix} \quad x=\begin{bmatrix}x\\ y\end{bmatrix} \quad Y=\begin{bmatrix}\tan(\theta_1)x_1 & -y_1\\ \tan(\theta_2)x_2 & -y_2\\ \vdots & \vdots\\ \tan(\theta_m)x_m & -y_m\end{bmatrix} \tag{2.14}$$

If we introduce formula (2.14) into the homogeneous sensor fusion model, then we can compute the position data of a human target in the pyroelectric sensors system.

2.3.2 Supplementary Method for Heterogeneous Sensor

As camera or pyroelectric sensors cannot measure the complete data of the target location separately, we use the redundant information to supply the incomplete position measurement until position measurements are integrated. Considering that we cannot get the satisfactory data of real-time human target tracking by pyroelectric sensors, measurement information can be supplemented by the camera which satisfies the real-time location and tracking of human target.

The pyroelectric sensor positions are $A(X_A, Y_A)$ and $B(X_B, Y_B)$, measurements of azimuth angle are β_A and α_B, and the human target coordinate is $Pt(X_{Pt}, Y_{Pt})$. At the same time, the $X-Y$ coordinate of the camera projection position is $C(X_C, Y_C)$. The distance between the human target and camera is L [14, 15]; so we can get that the distance between human target and three passive sensors are a, b, and L.

First, according to two-dimensional space, formula of distance between two points is:

$$d_i=\sqrt{(x-x_i)^2+(y-y_i)^2} \tag{2.15}$$

Three distance equations are established:

$$\begin{cases}(X_{Pt}-X_C)^2+(Y_{Pt}-Y_C)^2=L^2\\ (X_{Pt}-X_A)^2+(Y_{Pt}-Y_A)^2=a^2\\ (X_{Pt}-X_B)^2+(Y_{Pt}-Y_B)^2=b^2\end{cases} \tag{2.16}$$

So the coordinates of the human target can be obtained as follows:

$$\begin{bmatrix}X_{Pt}\\ Y_{Pt}\end{bmatrix}=\begin{bmatrix}2(X_A-X_C) & 2(Y_A-Y_C)\\ 2(X_B-X_C) & 2(Y_B-Y_C)\end{bmatrix}^{-1}\cdot\begin{bmatrix}X_A^2-X_C^2+Y_A^2-Y_C^2+L^2-a^2\\ X_B^2-X_C^2+Y_B^2-Y_C^2+L^2-b^2\end{bmatrix} \tag{2.17}$$

According to the pyroelectric node measured angles α and β_A, the following formula can be derived and the following results are deduced:

$$\begin{cases} \tan(\beta_A - 45) = \frac{d}{AT} \\ \tan(\alpha_B - 45) = \frac{d}{BT} \\ AT + BT = AB \\ AB = \sqrt{2} \cdot CA \\ \begin{cases} (OPt)^2 = L^2 + OC^2 \\ AT = \frac{\tan(\alpha_B - 45) \cdot \sqrt{2} \cdot AC}{\tan(\beta_A - 45) + \tan(\alpha_B - 45)} \end{cases} \\ BT = \sqrt{2} \cdot AC - AT \\ \begin{cases} a = \frac{AT}{\cos(\beta_A - 45)} \\ b = \frac{BT}{\cos(\alpha_B - 45)} \end{cases} \end{cases} \tag{2.18}$$

Substituting the above equation into the heterogeneous sensor fusion model, we can get the human target location data of pyroelectric and video mixing systems.

2.4 Simulation Examples

Assuming that the camera and PIR sensors track the same object, a camera, four PIR sensor nodes consist of dual-column and the sensor nodes with a field view of 360° are at the same platform, the synchronous sampling, data latency is zero. Mostly, the camera and pyroelectric node perform well. A PIR node has an azimuth measurement accuracy of 1 rad, accuracy of the camera is 0.5 m. Actually, PTR sensors work as pure azimuth observation. The camera in the process of tracking can be independent and can also cooperate with pyroelectric track together. The velocities deviation of PIR sensor nodes and the distance measured deviation of camera are related to the actual distance which is between the human body target and these fixed sensor nodes. Calculation and location methods would bring errors to the positioning result. However, these errors reflect the credibility of the node location. Therefore, we could implement the weighting of location node by using the errors, and the values of weighting would demonstrate the credibility so that we could improve the accuracy such as formula (2.9), W_i is the relative credibility, and the value is decided by the deviation and location precision. Before the simulation starts, it is necessary to set the weighting system. The values are determined by prior knowledge.

The PIR sensor tracking model is composed of four PIR sensor nodes with the structure of dual-column and the sensor nodes have a field view of 360°. The field of monitoring is 30 × 30 m and the measurement cycle is 1 s. First, to track by using the least square method with Gaussian noise, then, to implement the efficient tracking by using the expanded Kalman filter. The nodes have higher precision distribution, relatively higher weight, because the tracking precision of surrounding nodes is higher than the central nodes. The simulation results are Fig. 2.3 as follows:

1. The azimuth angle of observation noise variance is $\pi/180°$
2. The azimuth angle of observation noise variance is $2 \times \pi/180°$

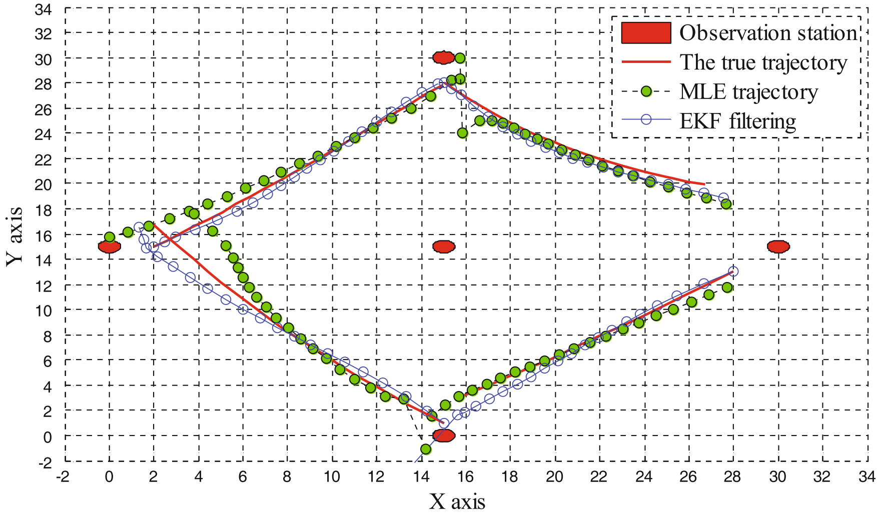

Fig. 2.3 Human tracking model

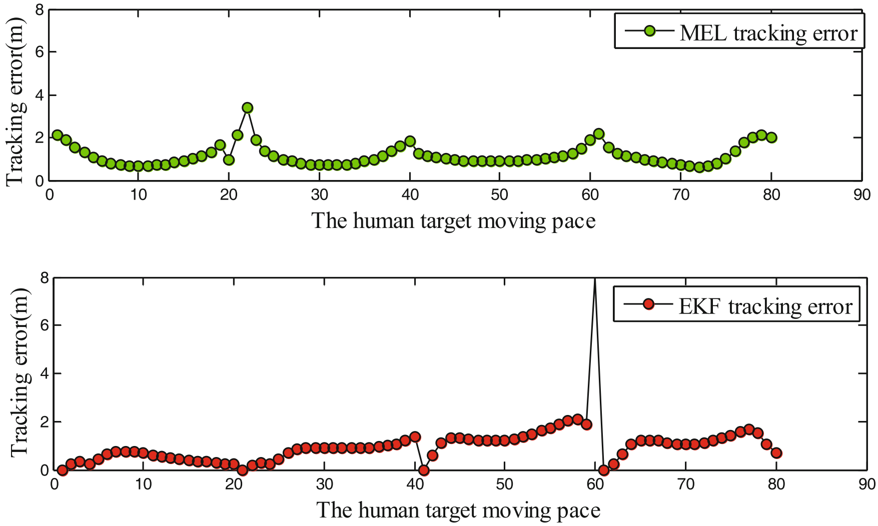

Fig. 2.4 Tracking error

With the increase of azimuth measurement noise variance, tracking error is increasing; the simulation results are shown in Fig. 2.4. After several tests, when azimuth measurement noise variance is 1°. As follows: *X* axis error mean of Least squares is 0.31 m and *Y* axis error mean is 0.42 m. After EKF filtering, *X* axis error mean is 0.22 m and Y axis error mean is 0.34 m. When azimuth measurement noise variance is 2°, *X* axis error mean of Least squares is 1.15 m and *Y* axis error mean

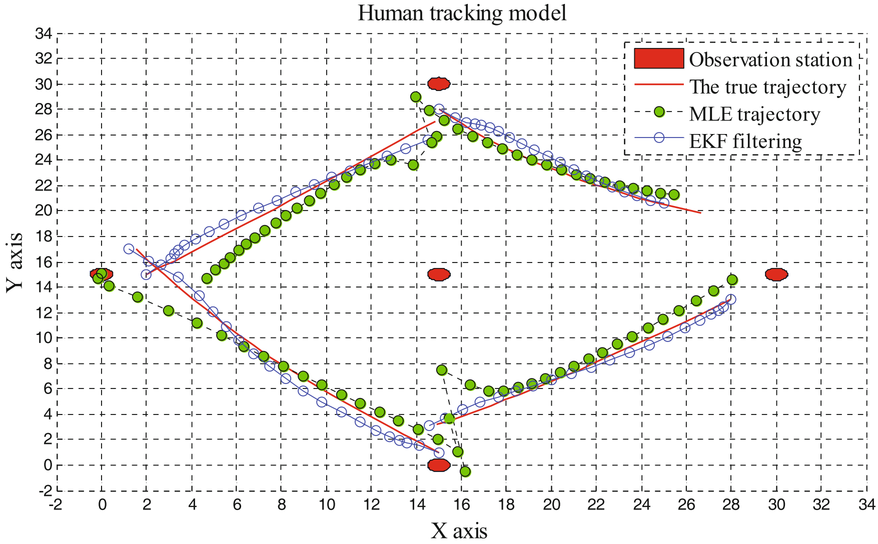

Fig. 2.5 Human tracking model

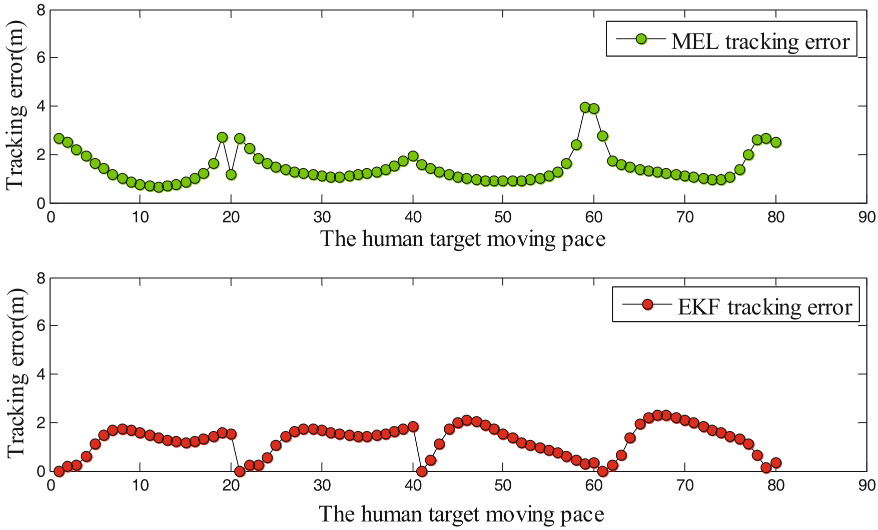

Fig. 2.6 Tracking error

is 1.43 m. After EKF filtering, X axis error mean is 1.01 m and Y axis error mean is 1.13 m (Figs. 2.5 and 2.6).

When pyroelectric nodes and cameras are used as a reference point to establish a fixed coordinate system, human target is doing the uniform motion in the mixing monitored area. Monitoring area is 30×30 m, measurement cycle is 1 s, the azimuth

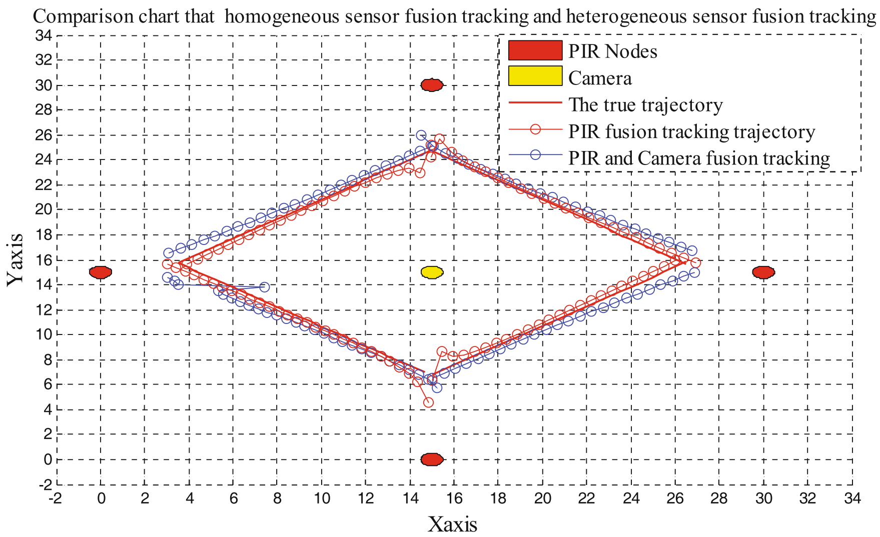

Fig. 2.7 Human tracking model

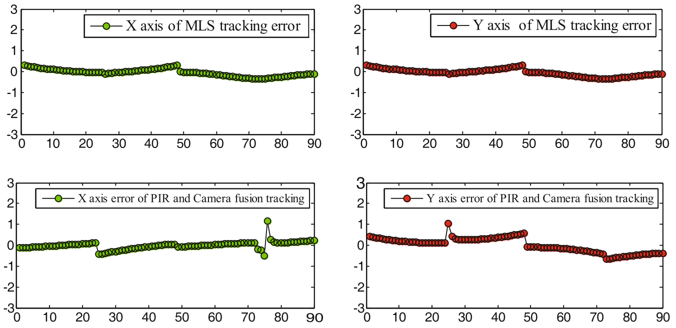

Fig. 2.8 Error-comparison chart of X-axis and Y-axis

angle of observation noise variance is $0.5 \times \pi/180°$, and distance of measurement noise variance is 0.5. After several simulation experiments, pyroelectric and camera fusion tracking error mean is 0.26 m. Tracking error mean of pyroelectric fusion with the camera is 0.37 m. The simulation results are Figs. 2.7 and 2.8. Comparing the hybrid tracking algorithm with $Qi.Hao.$ tracking algorithm, we can get the simulation results. It is shown in Figs. 2.9 and 2.10 simulation diagram.

Simulation area is 10×10 m, measurement cycle is 1 s, the azimuth angle of observation noise variance is $0.5 \times \pi/180°$, and the distance of measurement noise variance is 0.5.

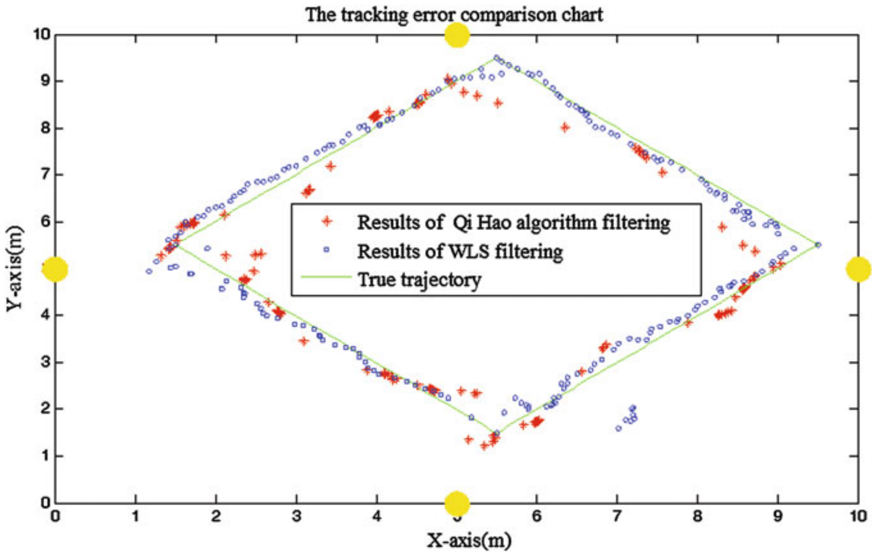

Fig. 2.9 Comparison chart of different tracking model

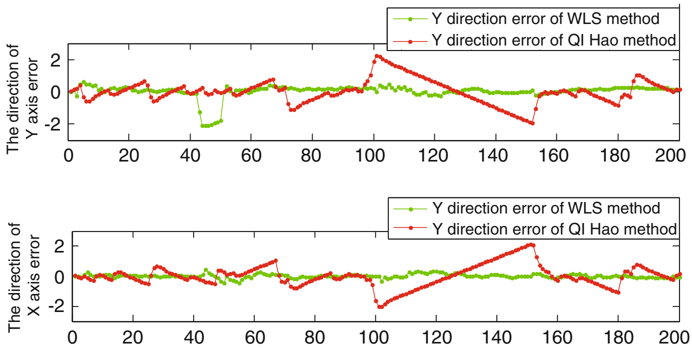

Fig. 2.10 Error-comparison chart of X-axis and Y-axis

2.5 Summary

This paper presents a system based on wireless pyroelectric infrared sensors network and video system. We have established the platform that realizes real-time human tracking and aggregates the information of distributed homogeneous sensors and heterogeneous sensors by using the weighted least square method, implementing the various patterns of human tracking. The hybrid monitoring system perfects the predecessor's research and solidifies the foundation of multihuman tracking. Meanwhile, the scheme presented in our paper would be more unprecedented because it combines the PIR sensor networks with the video systems.

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