Unmanned Patrol System Based on Kalman Filter and ZigBee Positioning Technology

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Abstract. In this paper, a security patrol method using UAV (Unmanned Aerial Vehicle) [1] as a carrier was proposed to solve the problems caused by traditional patrol methods such as low patrol frequency, low patrol efficiency and high security patrol cost. The ZigBee[2] module (the chip using CC2530 of ti) was adopted to locate the UAV. Also, the Kalman filter algorithm was used to reduce the influence of noise on the airborne patrol system to improve the positioning accuracy. This system was equipped with a ground station. and users could select nodes at the ground station for planned flight. The data exchanged between the ground station and the UAV through the XBee S3B module[3]. The UAV transmitted the images captured by the camera to the ground station in real time through the Athreros AR9271 WIFI launcher for security personnel to check in time. The ground station also handled the situation on the spot. As the UAV reached the area with poor GPS signal, we used ZigBee networking to locate and enhance the accuracy of positioning. Security patrols with UAVs(Unmanned Aerial Vehicles) as carriers improved traditional patrol methods to some extent. After a certain amount of data analysis, the results show that the ZigBee positioning data processed by Kalman filter are reliable.

1. Introduction
As Chinese society advances, the number and demand of enterprises are increasing, and the accompanying security problems are becoming more and more prominent. In some places such as large-scale construction sites, large industrial plants, and national strategic materials reserves, the high safety level is required. The existing patrol mode mainly uses a combination of manual patrol[4] and camera monitoring. However, this patrol method cannot avoid the problems such as the patrol
personnel's fatigue, distraction, low patrol frequency, laborious, and camera monitoring with dead angles. It is difficult to adapt to their security needs.

In order to solve this kind of security problem, this paper introduces a UAV patrol system, combined with the security patrol characteristics in such places. The system accurately identifies and tracks portraits, and handles special situations. However, GPS signals are poor in some areas where buildings are blocked, resulting in low positioning accuracy and limited requirements for UAV patrols. Considering that ZigBee has the characteristics of low power consumption, strong anti-interference and high reliability, it is used instead in the areas with poor GPS signals, to improve the positioning accuracy.

This paper introduces a UAV patrol system that can be operated according to a predetermined trajectory by positioning technology. The hybrid localization algorithm of ZigBee and GPS is designed. Based on the traditional GPS positioning technology, ZigBee positioning technology is supplemented, and then the measured positioning information is sent to the Kalman filter for denoising operation. Experiments prove that the Kalman filter algorithm effectively reduces the positioning error. The hybrid positioning[5] can solve the problem of GPS signal difference in some places.

2. System Composition—Quadrotor UAV Platform

2.1 Flight Control and Power Systems
The flight controller used by this system drone is Pixhawk, including six-axis gyroscope and barometers. It has many expandable interfaces, with powerful functions and good stability. The power system is composed of the Sunnysky 4110s model motor, the Hobbywing electronic governor, and a 17-inch blade. This kind of power ratio meets the standard of optimal power ratio, and it reduces system noise while increasing system efficiency. The rack is made of APC14x5.5MR or 15 inch carbon fiber, stable, light and reliable.

2.2 Image Transmission and Data Transmission Module
The communication between the UAV and the ground station is realized by the Mavlink protocol. The Xbee S3B module is the data transmission module on the UAV, which is responsible for the data communication between the UAV and the ground station. The XBee module, compatible with the ZigBee protocol and has networking function, adds a routing node to form a way of relaying data transmission, so that the accuracy of data transmission between buildings is more reliable. The image transfer protocol is Gstreamer[6] and transmits data over Wi-Fi. The Wi-Fi module's chip is an Athreros AR9271 IEEE-compliant 802.11b / g / n WLAN, and its high power allows Wi-Fi signal transmission to be wider and further.

2.3 Smart Camera Module
In order to solve the triaxial tilt of the UAV during flight, we designed a triaxial self-stabilizing pan-tilt, as shown in Figure (a). The triaxial rotatable pan/tilt counteracts the jitter generated as the drone is violently shaken, resulting in a higher quality image. The lens module uses the Sony IMX217 with an effective pixel count of approximately 13.51 million, performing well at night. The image control core uses the Raspberry Pi Model 3 B, which is connected to the camera module via the Camera_Bus port. The Athreros AR9271 chip connects the Raspberry Pi chip through the USB port to transmit image signals. The LED lights turn on during the night shooting. The Pixhawk controlled relay could switch the LED lighting mode.
2.4 ZigBee Module
The system consists of the 2.4GHz RF transceiver integrated with cc2530 chips produced by Texas Instruments (TI). The Atmaga_328 (Arduino UNO board) is used as the control chip. The P02 port and P03 port of the CC2530 chip are connected to the PD6 port and the PD7 port of the Atmaga_328 chip to realize data transmission. The M8N module receives signals such as GPS and Beidou. The RD and TD pins on the M8N module are connected to PC2 and PC3 on the Atmaga_328 chip for data transmission. The Atmaga_328 chip integrates the two positioning signals and then transmits the data to the Pixhawk flight control module via PD0 and PD1. Its connection is shown in Figure (b).

2.5 End User Design
The ground control platform software is developed using QT Creator based on the framework of the Pixhawk flight control system. In addition to displaying the UAV data, it also receives real-time video reception, one-button hover, spotlight control and alarm functions, which improves the efficiency of security patrol.
3. ZigBee Positioning Introduction

3.1 ZigBee Technology Introduction

ZigBee technology is a short-range wireless communication technology developed in recent years. It has low power consumption, low cost and easy application. It uses 2.4GHz as the main frequency band with spread spectrum technology. It is a name based on the IEEE 802.15.4 standard protocol. The ZigBee network consists of a coordinator, a router, and a terminal (see Figure (d)): The coordinator is the core of the network, responsible for constructing and maintaining the networking, and it has strong ability to process data; the router is responsible for relaying data - the relay between the terminal and the coordinator; the terminal is directly connected to the coordinator or connected to the coordinator through a router. The battery life of ZigBee devices often lasts for more than half a year, since the amount of data transmitted each time is small and the rate is low, and the time interval of signal sending and receiving is also short when each node is working. Besides, whenever ZigBee is not working, it is in a sleep state. Currently, ZigBee technology has been widely used in localization, detection and other fields.

![ZigBee networking structure](image)

Figure (d). ZigBee networking structure

![ZigBee structure protocol stack](image)

Figure (e). ZigBee structure protocol stack

The ZigBee protocol stack consists of Physical Layer (PHY), Media Access Control layer (MAC), Network layer (NWK) and Application layer (APL). The application layer is composed of Application...
Support Sublayer (APS), Application Framework (AF), ZigBee Device Object (ZDO), and user-defined application objects. The IEEE 802.15.4 standard defines the protocol scope of Physical Layer (PHY) and Media Access Control Layer (MAC), while the protocol scope of Network Application Layer (NWK) and Application Layer (APL) is determined by the ZigBee Alliance. The above figure (e) is ZigBee structure protocol stack.

The ZigBee chip used in this system is CC2530F256 produced by TI Company. It is a system-on-chip solution conforming to the IEEE802.15.4 standard and operates in the 2.4GHz band. We pre-arranged the ZigBee module in the preset UAV flight line and connected the power supply to form a ZigBee network for ranging and positioning. The cc2530 chip in the main ZigBee module on the UAV is responsible for receiving the RSSI information sent by each node in the networking. In Atmaga_328, the value of the distance d is converted by the RSSI value and the distance value, and then the maximum likelihood estimator is calculated, and the calculated value is presented in the form of coordinates. Subsequently, it is processed by the Kalman filter algorithm[7] in the Atmaga_328 chip, and the coordinate values and related information after filtering the noise are sent to the flight controller to achieve precise positioning. The following figure (f) is the flow of receiving data from the main ZigBee.

![Flow diagram](image)

Figure (f). The flow of receiving data from the main ZigBee

In this program, the MAC address is first screened to filter the interference of other slave systems through the ZigBee module, and then the corresponding MAC address and RSSI value are output. The computing core filters the MAC addresses again and classifies the RSSI values to form a customizable array of MAC addresses. As the data number meets the requirements in the array, the array is output to facilitate data processing and filtering.

3.2 RSSI Positioning Algorithm

We first obtained the the value of the Received Signal Strength (RSSI) by theoretical calculation, and the distance d between the host and the node by equations, and then used the maximum likelihood estimation method to determine the coordinates of the host in space.

3.2.1 Conversion of RSSI Value and Distance

Signal Transmission Loss Model in Vacuum:

\[
\begin{align*}
A &= \begin{bmatrix}
-2a_1 & -2h_1 & -2x_1 & 1 \\
-2a_2 & -2h_2 & -2x_2 & 1 \\
-2a_3 & -2h_3 & -2x_3 & 1 \\
-2a_4 & -2h_4 & -2x_4 & 1
\end{bmatrix}
\theta &= \begin{bmatrix}
x \\
y \\
z \\
R^2
\end{bmatrix},
B &= \begin{bmatrix}
\kappa_1^2 \\
\kappa_2^2 \\
\kappa_3^2 \\
\kappa_4^2
\end{bmatrix}
\end{align*}
\]

(1)

where d denotes the distance between the receiving node and the source node; \( f \) denotes the frequency (in MHz); \( k \) denotes the parameter of the path loss. Considering the complexity of the real
environment and the dispersion of nodes, the above model can be corrected to a log-normal distribution model:

\[ PL(d) = PL(d_0) + 10k \lg\left(\frac{d}{d_0}\right) + X_0 \]  

(2)

where, \( PL(d) \) denotes the strength of the signal after propagation \( d \), and its unit is dBm;
\( X_0 \) denotes a random variable, it obeys a Gaussian distribution, of which the mathematical expectation is \( \mu \), and the variance is \( \sigma^2 \), with an average of 0, meanwhile, its standard deviation range is 4 to 10;
\( k \) denotes a factor of path loss ranging from 2 to 4.

When \( d = 1 \), we get the value of RSSI:

\[ RSSI = (10n \lg d + A) + pt \]  

(3)

where \( A \) denotes the absolute value of RSSI when the distance between two nodes is 1 meter, and the optimal range is between 45 and 49; \( pt \) denotes the influencing factor, which obeys the normal distribution;

### 3.2.2 Maximum Likelihood Estimation Method to Determine Spatial Coordinates

In space, three circles determine a point. If the distance between the host and the three nodes is known, plus the coordinates of the three nodes known in the space, the coordinates of the host can be calculated by a certain calculation method. Set the coordinates of the positioning node to \((x, y, z)\), and the coordinates of the four reference nodes and the RSSI values respectively correspond to:

\[ (a_1, b_1, c_1), RSSI_1; \]
\[ (a_2, b_2, c_2), RSSI_2; \]
\[ (a_3, b_3, c_3), RSSI_3; \]

By the equation:

\[ RSSI = 10n \lg d + A \]  

(4)

Calculate the distance between these nodes and the coordinates of the master node and bring them into the equation. Then, we get

\[ (x-a_i)^2+(y-b_i)^2+(z-c_i)^2 = d_i \]

Suppose:

\[ r_i^2 = d_i^2 - (a_i^2 + b_i^2 + c_i^2) \quad i = 1, 2, 3, 4, R^2 = x^2 + y^2 + z^2 \]

We can simplify the above equation as:

\[ \begin{bmatrix}
-2a_1 & -2b_1 & -2c_1 & 1 \\
-2a_2 & -2b_2 & -2c_2 & 1 \\
-2a_3 & -2b_3 & -2c_3 & 1 \\
-2a_4 & -2b_4 & -2c_4 & 1 \\
\end{bmatrix}
\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} r_1^2 \\ r_2^2 \\ r_3^2 \\ r_4^2 \end{bmatrix} \]

Suppose:

\[ A = \begin{bmatrix}
-2a_1 & -2b_1 & -2c_1 & 1 \\
-2a_2 & -2b_2 & -2c_2 & 1 \\
-2a_3 & -2b_3 & -2c_3 & 1 \\
-2a_4 & -2b_4 & -2c_4 & 1 \\
\end{bmatrix}, \theta = \begin{bmatrix} x \\ y \\ z \end{bmatrix}, B = \begin{bmatrix} r_1^2 \\ r_2^2 \\ r_3^2 \\ r_4^2 \end{bmatrix} \]

then, we get

\[ A\theta = B \]

Finally, we determine the coordinates of the point:

\[ \hat{\theta} = (A^T A)^{-1} A^T B \]  

(6)
4. Kalman Filter Algorithm for Processing Data

The RSSI-based distance measurement is extremely susceptible to interference noise. The RSSI measurement distance alone cannot meet the positioning accuracy requirements of the UAV. Kalman filter is an effective algorithm for Gaussian process optimal filtering. The performance is better when the object model is accurate enough and the system state and parameters do not change abruptly. Therefore, the positioning accuracy is enhanced using the filtering function of the Kalman filter to reduce the noise influence on the system, combining the Kalman filter algorithm with the above RSSI positioning algorithm.

First, the state equation of the displacement and velocity of the system is established and discretized according to the above positioning information. The state equation of the positioning system is

\[
X_{k+1} = AX_k + W_k
\]

(7)

\[
S_k = CX_k + V_k
\]

(8)

Where \( X_k \) denotes the robot positioning information to be optimized, \( X = \begin{bmatrix} x_k & y_k & V_x & V_y \end{bmatrix}^T \), \( x_k, y_k \) and \( V_x, V_y \) are the unique and velocity estimates of the UAV in both directions in the XY coordinate system at time \( k \); \( A \) denotes the system matrix; \( S_k \) denotes the observation vector, which contains the positioning information of the UAV. \( S_k = [s_x, s_y]^T \), \( s_x, s_y \) are the observations of the UAV in two directions in the XY coordinate system at time \( k \), which are the coordinates measured by the maximum likelihood estimation method in the system based on the RSSI value. \( C \) denotes the output matrix; \( W_k \) and \( V_k \) are state noise and observed noise, respectively, and satisfy \( E[W_k] = E[V_k] = 0 \), \( E[W_k W_k^T] = Q \), \( E[V_k V_k^T] = R \) (\( Q \) and \( R \) are the state noise matrix and the observed noise matrix, respectively), that is, \( W_k \) and \( V_k \) are independent zero-mean white noise sequences.

The statistical properties of the initial value \( X(0) \) of the state vector are given as:

\[
E[X(0)] = \mu_0
\]

(9)

\[
\text{Var}[X(0)] = E\left[\left(X(0) - \mu_0\right)^2\right] = P_0
\]

(10)

Kalman filter calculation is divided into

(1) Prediction Process of Kalman filter equation:

State one step prediction:

\[
\hat{X}_{k, k-1} = A \hat{X}_{k-1, k-1}
\]

(11)

One-step prediction error variance matrix:

\[
P_{k, k-1} = AP_{k-1, k-1}A^T + Q
\]

(12)

(2) Correction Process of Kalman Filter Equation:

Filter Gain Matrix:

\[
K_k = P_{k, k-1}C^T\left[CP_{k, k-1}C^T + R\right]^{-1}
\]

(13)

State estimate:

\[
\hat{X}_{k,k} = \hat{X}_{k,k-1} + K_k(S_k - C\hat{X}_{k,k-1})
\]

(14)

Estimated error variance matrix:

\[
P_{k,k} = [1 - K_k C]P_{k,k-1}
\]

(15)

The two-dimensional model of the UAV position movement is:

\[
\begin{bmatrix}
    x_k \\
    y_k \\
    V_x^k \\
    V_y^k
\end{bmatrix} =
\begin{bmatrix}
    1 & 0 & \Delta t & 0 \\
    0 & 1 & 0 & \Delta t \\
    0 & 0 & 1 & 0 \\
    0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    x_{k-1} \\
    y_{k-1} \\
    V_x^{k-1} \\
    V_y^{k-1}
\end{bmatrix}
+ 
\begin{bmatrix}
    \Delta t & 0 & 0 & 0 \\
    0 & \Delta t & 0 & 0 \\
    0 & 0 & 1 & 0 \\
    0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    w_k^x \\
    w_k^y \\
    w_{k-1}^x \\
    w_{k-1}^y
\end{bmatrix}
\]
where $\Delta t$ denotes the state update time interval, that is, the sampling interval.

The observation matrix is:

$$
\begin{bmatrix}
S^x_k \\
S^y_k
\end{bmatrix} =
\begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
x_k \\
y_k
\end{bmatrix} +
\begin{bmatrix}
v^x_k \\
v^y_k
\end{bmatrix}
$$

where $v^x_k$ and $v^y_k$ denote observed noises.

The Kalman filter process is performed in an Arduino board (i.e., Atmega 328). The Arduino receives the Zigbee positioning data information and processes it every $\Delta t$ time. After processing by the Kalman filter, the (x, y) value is sent to the flight control to obtain more accurate positioning information. The flight control also sends the data to the ground station through the Mavlink protocol to achieve data convergence.

5. **System Testing and Simulation**

Figure (g) shows the real trajectory of the UAV and the trajectory after the Kalman filter processing in the case of the node distribution. The positioning trajectory after Kalman filter processing is close to the real trajectory. In Figure (h), the positioning error of the maximum likelihood estimation method processed by Kalman filter is smaller than that of the maximum likelihood estimation method using only RSSI. It indicates that the Kalman filter algorithm could effectively reduce the error of the general positioning algorithm (such as the maximum likelihood estimation method). Figure (i) shows the relationship between the positioning average error of the Kalman filter and the maximum likelihood estimation method and the number of nodes, as the values of the standard deviation $\sigma$ of the random variable $X_0$ are 0.5 and 1. It can be seen from the Figure (i) that under the same conditions, the positioning average error of the Kalman filter algorithm is much smaller than that of the maximum likelihood estimation method. It indicates that the Kalman filter algorithm could reduce the positioning error; when the standard deviation $\sigma$ is 0.5, the positioning average error of the two algorithms is smaller than that of the two algorithms when $\sigma$ is 1; in addition, the average positioning error of the two algorithms decreases as the number of positioning nodes increases.
6. Conclusions

In this paper, a patrol UAV was designed using the ZigBee positioning algorithm processed by Kalman filter. The UAV was equipped with monitoring, lighting and hailing device. The UAV transmitted information to the ground station through Mavlink protocol, and the ground station controlled the UAV to fly autonomously along a preset route. We placed ZigBee nodes on our flight path for positioning. The CC2530 module on the UAV was input to Atmaga_328 through the serial port for Kalman filter processing, after receiving the RSSI value from three or more nodes. The positioning information processed by Kalman filter has a certain prediction and correction effect on the original information, which greatly reduces the error caused by noise and improves the stability of the system.

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