Distributed cooperative formation of multiple unmanned ships based on KF

Wang Liu, Xiafu Lv
Automation, Chongqing University of Posts and Telecommunications, Chongqing, 400065, China
*Corresponding author’s e-mail: s180331039@stu.cqupt.edu.cn

Abstract: To study the cooperative formation of unmanned ships, and for the influence of noise signals in multiple sensors of multiple unmanned ships, a formation mode based on distributed Kalman filtering is proposed. The position information of the main ship is determined first, and the auxiliary ship sets the desired position of the auxiliary ship as the target of the auxiliary ship according to the position information of the main ship, and finally keeps the formation to move toward the target. The target tracking of single unmanned ship and multiple unmanned ship systems is simulated. The research results show that not only the estimated trajectory of the single unmanned ship is greatly optimized, but the trajectory of each unmanned ship in the multiple unmanned ship system is also very good. It fits the expected trajectory very well and meets the expected requirements.

1. Preface
In recent years, as the goal of "Industry 4.0" has been proposed, and the rapid development of artificial intelligence, computer science and unmanned technology, unmanned ships have become the trend of intelligent ship development. Because unmanned ships have the advantages of high autonomy, simple assembly, flexible use, and low cost[1], unmanned ships are not only widely used in military applications, but also developed rapidly in civilian use. In the military field, unmanned ships have developed rapidly. Ships are mainly used to carry out mine clearance, anti-submarine warfare and anti-special warfare dangerous missions[2]. In non-military applications, unmanned ships are used for rivers and seas cruising, rescue and resource supply[3]. Among these practical tasks, a single unmanned vessel cannot be completed. Therefore, a multi-unmanned vessel system is introduced. With the coordination and cooperation of multiple unmanned vessels, it is possible to complete complex tasks that cannot be accomplished by a single unmanned vessel. The most basic contradiction that hinders the coordinated operation of multiple unmanned ships lies in the formation control of unmanned ships. The so-called formation control refers to maintaining a certain formation while many unmanned ships reach a destination while adapting to the constraints of the environment[4]. Because the application scenarios of the multi-unmanned ship system are different, the formation of the multi-unmanned ship system and the control method of the formation are different[5].

2. System modeling

2.1 Single unmanned ship model
First consider the model of a single unmanned ship tracking target, as shown in Figure 1. Through dead reckoning, a model between the unmanned ship and the target can be established. Under normal
circumstances, the unmanned ship can measure the distance between the target and itself, and obtain its own heading angle through the inertia link. Then the system model of a single unmanned ship is as follows:

![Figure 1. The relative motion relationship of unmanned ship tracking target](image)

Displacement $s(k)$, velocity $u(k)$ and acceleration $a(k)$. It can be seen from the uniform acceleration formula:

$$s(k+1) = s(k) + u(k)T_s + 0.5T_s^2a(k)$$

$$s(k+1) = s(k) + T_s^2a(k)$$

(1)

The acceleration is the combined acceleration of maneuvering acceleration and random acceleration (noise). Then the nonlinear state equation of the system:

$$P(k+1) = \begin{bmatrix} X_u(k+1) \\ V_u(k+1) \\ Y_u(k+1) \\ V_y(k+1) \end{bmatrix} = \begin{bmatrix} X_u(k) + V_y(k)T_s \\ V_u(k) \\ Y_u(k) + V_y(k)T_s \\ V_y(k) \end{bmatrix} + a_{k+1}(k)$$

(2)

Among them $T_s$ is the sampling period of the system, $(X_u, Y_u)$ and $(V_x, V_y)$ are the position and velocity of the ship in sequence; $a(k)$ are the total acceleration of the ship; $X_u, Y_u$ are the $x$ and $y$ directions respectively, $q$ is Gaussian white noise with zero mean value.

Then the solvable unmanned ship tracking target observation equation is:

$$Z(k) = C \begin{bmatrix} X_u(k) \\ \dot{X}_u(k) \\ Y_u(k) \\ \dot{Y}_u(k) \end{bmatrix} + v_{2n}(k)$$

(3)

### 2.2 Multi-unmanned ship system model

In the previous section, the relationship between the various modules of the unmanned ship and the establishment of a single unmanned ship system model were introduced. Based on the single unmanned
ship target tracking model, a system model of multiple unmanned ship formations was established:

\[
\begin{align*}
\dot{1}f & = A(1)f + B_1u_1 + q_1 \\
Z_1 & = C_1f + v_1
\end{align*}
\]

As shown in Figure 2, a three-ship cooperative formation model is established, where \( l \) is the main ship, \( f_1 \) and \( f_2 \) are auxiliary ships; their positions are \((x_{f11}, y_{f11})\), \((x_{f21}, y_{f21})\), and \((x_{f22}, y_{f22})\), respectively. \( f_1 \), \( f_2 \) are the expected position of the assistant ship according to the main ship in the formation. Among them, \( f_1 \) has reached the desired position, that is, \((x_{f11}, y_{f11}) = (x_{f11}, y_{f11})\); the unmanned ship \( f_2 \) has not reached its desired position.

In Figure 2, a and b are the angles between the line connecting the main ship at the desired position c and d and the vertical direction of the main ship's course.

In the movement, the main ship tracks the target, and the auxiliary ship tracks the left and right desired positions of the main ship to form a formation; the more complicated problem of multiple unmanned ships tracking the target can be transformed into a simple problem of each ship chasing the target. This method can not only greatly reduce the overall error of the multi-unmanned ship system, but also enable each ship in the system to reach its desired position faster.

3. Distributed co-location algorithm

3.1 Main ship target tracking

The standard Kalman equation can be obtained by analyzing the motion of the main ship as follows:

\[
P(k) = AP(k - 1) + Bu(k - 1) + q(k - 1)
\]
\[
Z(k) = CP(k) + v(k)
\]

From equation (4), the state transition equation and the observation equation are (5) and (6):

\[
\begin{bmatrix}
X_1(k) \\
V_1(k) \\
Y_1(k) \\
V_2(k)
\end{bmatrix} = \begin{bmatrix}
X_1(k - 1) \\
V_1(k - 1) \\
Y_1(k - 1) \\
V_2(k - 1)
\end{bmatrix} + \begin{bmatrix}
a_{x1}(k) \\
a_{y1}(k)
\end{bmatrix}
\]

Figure 2. The relative motion of the three unmanned ships
Then the state transition matrix and observation matrix can be solved by equations (5) and (6):

\[
\begin{bmatrix}
Z_x(k) \\
Z_y(k)
\end{bmatrix} = 
\begin{bmatrix}
X_i(k) \\
Y_i(k) \\
V_x(k) \\
V_y(k)
\end{bmatrix} + V(k)
\] (6)

Then the state transition matrix and observation matrix can be solved by equations (5) and (6):

\[
A = 
\begin{bmatrix}
1 & T_s & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & T_s \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (7)

\[
C = 
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\] (8)

### 3.2 Tracking the desired position of the deputy ship

Through the analysis of the main ship's motion in the previous section, combined with equation (4), the state transition equation and observation equation of the secondary ship can be obtained as equations (9) and (10) respectively.

\[
\begin{bmatrix}
X_{f1}(k) \\
Y_{f1}(k) \\
V_{x1}(k) \\
V_{y1}(k)
\end{bmatrix} = A_i \begin{bmatrix}
X_{f1}(k-1) \\
Y_{f1}(k-1) \\
V_{x1}(k-1) \\
V_{y1}(k-1)
\end{bmatrix} + a_{x1+1}(k)(i = 1, 2)
\] (9)

\[
\begin{bmatrix}
Z_x(k) \\
Z_y(k)
\end{bmatrix} = C \begin{bmatrix}
X_i(k) \\
Y_i(k) \\
V_x(k) \\
V_y(k)
\end{bmatrix} + V(k)
\] (10)

The expected positions of the two auxiliary ships are calculated by the position of the main ship, and the positional relationship in Figure 2 can be obtained:

\[
\begin{align*}
x_{j1} &= x_i - \text{dist} \sin(\theta + \hat{\theta}_1) \\
y_{j1} &= y_i + \text{dist} \cos(\theta + \hat{\theta}_1) \\
x_{j2} &= x_i + \text{dist} \sin(\theta - \hat{\theta}_2) \\
y_{j2} &= y_i - \text{dist} \cos(\theta - \hat{\theta}_2)
\end{align*}
\] (11) (12)

From equations (9) and (10), the state transition matrix and observation matrix of the desired position of the auxiliary ship on both sides of the main ship can be obtained:

\[
A_{f1} = A_{f2} = 
\begin{bmatrix}
1 & T_s & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & T_s \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (13)

\[
C_{f1} = C_{f2} = 
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\] (14)
4. Simulation analysis

4.1 Single unmanned ship positioning model
Determine the path of the target movement, use MATLAB software to simulate and verify the single unmanned ship, and then use the KF method to simulate. The simulation time is 80s, and the sampling period is $T_s = 1s$. Figure 4 is a comparison diagram of the error effect before and after using KF filtering, the error after filtering will be much smaller than the error before filtering. Figure 5 shows the real path of the unmanned ship, the observation path, and the expected path after KF processing. From Figure 5, we can know that the observation position deviation before KF filtering is large, and the filtered target position is always maintained at the true position. In the near area.

![Figure 3. Error comparison before and after KF filtering](image3)

![Figure 4. Moving target tracking trajectory](image4)

4.2 Cooperative positioning model of multiple unmanned ships
From the MATLAB simulation, the path graph of multiple unmanned ships without feedback can be obtained as shown in Figure 5. From Figure 5, it can be seen that there is a large amount of overlap between the estimated positions of multiple unmanned ships when there is no feedback, that is, there is no The formation of people and ships is too poor.
Figure 5. Multiple unmanned ships without feedback positioning

After processing by using the KF filter, the simulation graph shown in Figure 6 is obtained. It can be seen from Figure 6 that during the movement of multiple unmanned ships, the position estimates of each ship are scattered in the close area of its true trajectory, namely The formation of multiple unmanned ships can be well maintained

Figure 6. KF processing and positioning of multiple unmanned ships

5. Conclusion
Aiming at the excessive formation error of multiple unmanned ship formation squadrons, this paper proposes a distributed co-location method based on the KF method, so that each ship has its own tracking target, and there will only be one for each ship. Small errors, there will be no superposition of errors on the error, the problem of tracking the target of the entire large multi-unmanned ship system is broken down into the target tracking problem of each unmanned ship, and the entire unmanned ship system tracking target is not reduced. While causing errors to accumulate, it also effectively reduces the complexity of the entire unmanned ship system, and has a good formation maintaining effect. In practice, the fusion of multiple sensor information can better obtain environmental information and the communication delay of unmanned ships. These issues need to be studied in depth.
References

[1] Guanghao Lv, Zhouhua Peng, Dan Wang. (2018) Target task allocation of unmanned vessel formation reconstruction[J]. Chinese Ship Research, 13(06): 103-108.

[2] Yingbin Chen. (2019) The development status of unmanned ships and an overview of key technologies[J]. Science and Technology Innovation, 000(002): P. 60-61.

[3] Biao Wang, Bo Li, Min Gao. (2019) Overview of Cooperative Control Strategies for Unmanned Vessels[J]. China Water Transport (the second half of the month), 19(02): 9-11.

[4] Yanmin Lei, Zhibin Feng, Jihong Song. (2008) Simulation Research on Behavior-based Multi-robot Formation Control[J]. Journal of Changchun University, 18(008): 40-44.

[5] Zhiqiang Cao, Bin Zhang, Min Tan. (2001) Real-time formation maintenance of multiple mobile robots based on behavior[J]. High Technology Communications, 2001(10): 77-80.

[6] Xin Zhang, Yudong Liu, Yongfeng Ju. (2011) A multi-robot collaborative positioning method based on distributed EKF[J]. Computer Simulation, 028(009): 219-222.