Underwater Target Tracking with Autonomous Underwater Vehicle

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***Abstract*—This paper addresses the problem of target tracking with autonomous underwater vehicle (AUV) on the horizontal plane. This paper focuses on some key methods such as target movement state estimation, target tracking guidance, target tracking control and tracking strategy. Unscented Kalman filter (UKF) is applied to estimate the movement state of the target. The kinematics and dynamics of AUV are presented, the pure pursuit (PP) guidance is introduced to settle the tracking errors, the heading controller and velocity controller are designed using PID theory individually based on the tracking errors and tracking strategy is designed to satisfy the demand of target tracking with AUV. The results of simulation experiment proved that UKF can estimate the target state effectively and the controller and the tracking strategy for AUV are useful.**

Keywords-Autonomous Underwater Vehicle; Target Tracking; Unscented Kalman Filter; Pure Pursuit Guidance

I. INTRODUCTION

Underwater target tracking is an important research direction within several years. AUV is one of the most effective tools applied to do this work, the technology of which is developed in recent forty years. The key problems of underwater target tracking with AUV include target movement state estimation, target tracking guidance, tracking control and tracking strategy for AUV. This paper aims to solve the problems above.

More and more researchers pay attention to underwater target tracking. [1][2] presented a method for estimating the movement and orientation states of a tagged shark as the target with AUV. A state estimator with particle filter (PF) was designed to estimate the states of the shark and which is combined with an active control system to overcome the ambiguity in the sign of the bearing angle. In the tracking system with AUV, the first part is how to estimate the states of the target. Estimators based on Kalman Filter (KF) are used deeply on target tracking. In recently years Unscented Kalman Filter (UKF) is preferred because of its higher precision than Extended Kalman Filter (EKF) and its lower computation complexity than PF which make UKF more efficient in real-time tasks. [3] presented the simulated results of tracking nonlinear, ballistic and reentry targets with UKF and EKF. The results give more supporting points to use UKF for nonlinear target tracking.

The second key point of underwater target tracking with AUV is the controller design for AUV. And before which guidance law should be determined to compute tracking errors. Fossen introduced three guidance laws which were used in missile guidance for marine vessel guidance including line of sight (LOS), pure pursuit (PP) and constant bearing (CB) [4][5]. From then on the guidance laws are widely used in movement controller design of surface vessel and underwater vehicle. Based on the definition of tracking errors controller play an important role in target tracking which will influence the tracking result. Point stabilization, trajectory tracking and path-following control are advanced nonlinear motion control methods for marine vehicle in a few years [6]. [7] combined trajectory planer and tracking control using backstepping for underactuated AUV on the horizontal plane. [8] proposed a nonlinear adaptive path following strategy for underactuated AUV using Lyapunove's direct method , backstepping and parameter projection techniques. But as far there is not an efficient control method for target tracking with AUV.

In this paper, UFK is applied to estimate the movement state of the target. The kinematics and dynamics of AUV are presented, the PP guidance is introduced to settle the tracking errors, the heading controller and velocity controller are designed with PID individually based on the tracking errors and tracking strategy is designed to satisfy the demand of target tracking with AUV.

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The rest of this paper is organized as follows. Section II introduced the inertial frame and body frame, the kinematics and dynamics of underactuated AUV on the horizontal plane. UKF is introduced in details in section III. Section IV contains the PP guidance law, controller design and tracking strategy individually. Finally, in section V the results of simulation experiment are presented and discussed.

II. VEHICLE MODELING

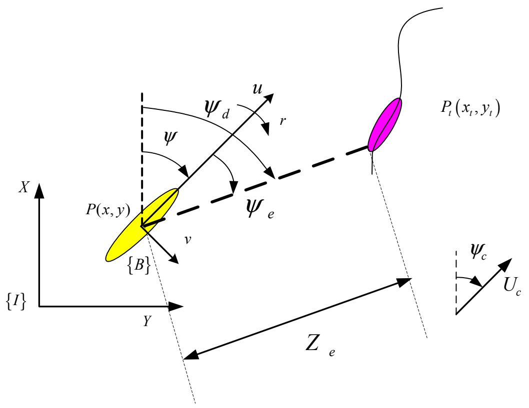

Fig.1 Frames

The inertial frame $\{I\}$ and body fixed frame $\{B\}$ are depicted in Fig. 1. P is the position of AUV, P_t is the target position, ψ is the heading of AUV and ψ_d is the desired heading in inertial frame. And u is surge speed, v is sway speed and r is the yaw speed of AUV in body frame [4]. U_c is the magnitude of the speed of constant current and ψ_c is the direction of current.

This paper adopts the INFANTE AUV [9] model as research object. The kinematic and dynamitic equations with current can be written as follows [7].

$$\dot{x} = (u_c + u_r)\cos\psi - (v_c + v_r)\sin\psi \quad (1)$$

$$\dot{y} = (u_c + u_r)\sin\psi + (v_c + v_r)\cos\psi \quad (2)$$

$$\dot{\psi} = r \quad (3)$$

$$\dot{u}_r = \frac{m_{22}}{m_{11}} v_r r - \frac{X_u}{m_{11}} - \frac{X_{u|u|}}{m_{11}} u_r |u_r| + \frac{1}{m_{11}} F \quad (4)$$

$$\dot{v}_r = -\frac{m_{11}}{m_{22}} u_r r - \frac{Y_v}{m_{22}} v_r - \frac{Y_{v|v|}}{m_{22}} v_r |v_r| \quad (5)$$

$$\dot{r} = \frac{m_{11} - m_{22}}{m_{22}} u_r v_r - \frac{N_r}{m_{33}} r - \frac{N_{r|r|}}{m_{33}} r|r| + \frac{1}{m_{33}} T \quad (6)$$

Where u_r and v_r are velocities relative current. m_{11}, m_{22} and m_{33} present the combined inertia and added mass terms, $X_{\{\}}$, $Y_{\{\}}$,and $N_{\{\}}$ are classical hydrodynamic derivatives. F and T denote the forward force and yaw torque applied to the AUV, and $[u_c \quad v_c]^T$ is the vector of constant current speed which can be written as

$$u_c = U_c \cos(\psi_c - \psi) \quad (7)$$

$$v_c = U_c \sin(\psi_c - \psi) \quad (8)$$

III. UNSCENTED KALMAN FILTER

How to get the movement state of the target in rectangle coordinate without introducing new noise from measurement in polar frame is the first problem to be solved for target tracking. UKF using unscented transform to meet the nonlinearity of the observation function instead of linearization works better than EKF.

The equations of UKF are formed as follows[3][10]:

$$\chi_i = \begin{cases} \bar{x}, i = 0 \\ \bar{x} + (\sqrt{(n+\lambda)P_x})_i, i = 1, \cdots, n \\ \bar{x} - (\sqrt{(n+\lambda)P_x})_i, i = n+1, \cdots, 2n \end{cases} \quad (9)$$

$$W_i^{(m)} = W_i^{(c)} = \begin{cases} \lambda / (n+\lambda), i = 0 \\ 1/[2(n+\lambda)], i = 1, \cdots, 2n \end{cases} \quad (10)$$

$$\chi(k-1) = \{\hat{x}(k-1), \hat{x}(k-1) + [\sqrt{(n+\lambda)P_x(k-1)}]_i, \hat{x}(k-1) - [\sqrt{(n+\lambda)P_x(k-1)}]_i\}, (i = 1, \cdots, n) \quad (11)$$

$$\chi_i^-(k) = f[\chi_i(k-1)](i = 0, \cdots, 2n) \quad (12)$$

$$\hat{x}^-(k) = \sum_{i=0}^{2n} W_i^{(m)} \chi_i^-(k) \quad (13)$$

$$P_x^-(k) = \sum_{i=0}^{2n} W_i^{(c)} [\chi_i^-(k) - \hat{x}^-(k)] [\chi_i^-(k) - \hat{x}^-(k)]^T + Q_k \quad (14)$$

$$\hat{x}(k) = \hat{x}^-(k) + K[z(k) - \hat{z}^-(k)] \quad (15)$$

$$P_x(k) = P_x^-(k) - KP_z(k)K^T \quad (16)$$

$$K = P_{xz}(k) P_z^{-1}(k) \quad (17)$$

$$\hat{z}^{-}(k)=\sum_{i=0}^{2n}W_i^{(m)}h[\chi_i^{-}(k)] \tag{18}$$

$$P_z(k)=\sum_{i=0}^{2n}W_i^{(c)}\{h[\chi_i^{-}(k)-\hat{z}^{-}(k)]\}\{h[\chi_i^{-}(k)-\hat{z}^{-}(k)]\}^T+R(k) \tag{19}$$

$$P_{xz}(k)=\sum_{i=0}^{2n}W_i^{(c)}\{\chi_i^{-}(k)-\hat{x}^{-}(k)\}\{h[\chi_i^{-}(k)-\hat{z}^{-}(j)]\}^T \tag{20}$$

Where χ_i is the Sigma point and χ_i^{-} is the prediction, $\hat{x}$ is the estimated state, P_z is the covariance and P_{xz} is the cross covariance. $\hat{x}$ is the desired state estimation of the target.

IV. TRACKING CONTROL

A. Guidance

Guidance is introduced to target tracking by marine vehicle by Fossen including line of sight, pure pursuit and constant bearing. Pure pursuit (PP) guidance is adopted to compute the tracking errors in this paper. PP belongs to the two-point guidance laws, and the inter captor aligns its velocity to the target directly[5]. Shown in Fig. 1, Z_e is the distance between target and AUV, ψ_e is the heading error.

B. Controller Design

So far controller based on PID is still the most useful and popular for target tracking control for AUV. The heading controller and velocity controller are shown in Fig. 2.

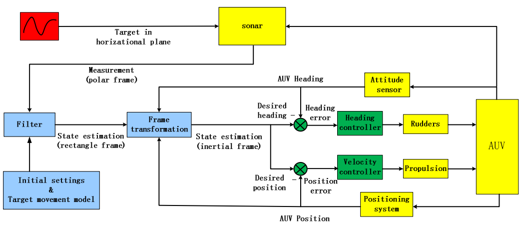

Fig. 2 Flow of the simulation experiment

C. Tracking Strategy

Firstly, as shown in Fig.3, l_m is the measurement range of the sonar, l_d is the desired distance between target and AUV and l_l is the limit distance between of target and AUV. If the distance between target and AUV is shorter than l_l AUV may be detected by target which means the target tracking mission will turn to a failure.

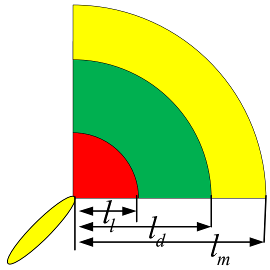

Fig.3 l_l, l_d and l_m

There are three constraints for target tracking with AUV[10]:

The distance Z_e between target and AUV is shorter than the measurement range l_m of sonar;

1) Z_e is longer than the limit distance l_l in which AUV will be discovered by target;

2) To make sure that the power consumption is minimum.

To satisfy the constraints above tracking strategy is designed as following.

The desired distance between target and AUV is defined as l_d. If $Z_e \le l_d$, AUV should decrease surge, setting $F=0$; or AUV should increase its surge to track target to make sure $l_l < Z_e \le l_m$.

V. SIMULATION EXPERIMENT

In order to investigate the effect the designed method above, simulation experiments were carried out. The flow of experiment is shown in Fig. 2. The target moves around a circle which generates a trajectory (red part), the relative distance and angle are measured by sonar in polar frame with noise, UKF is used to estimate the position of the target in body frame and the position is transformed to inertial frame by frame transformation module (blue part); the tracking errors are computed by PP guidance; heading controller and velocity controller generate control force and torque witch force AUV to track target (green part).

The initial conditions of the experiment are listed as follows.

Target moves along a circle trajectory which can be written as

$$\begin{cases} x_t = 300 + 100\sin(t\pi / 180 / 4) \\ y_t = 200 + 100\cos(t\pi / 180 / 4) \end{cases} \quad (21)$$

The initial state of u, v, r, F, and T of AUV are all zero. The start point of AUV is $(270, 310)$, $\psi = \arctan(10/-30)$, $U_c = 0.1m/s$ and $\psi_c = \pi/4$, l_m =60m, l_d =40m, l_l =20m.

The results of the simulation experiment are shown as follows:

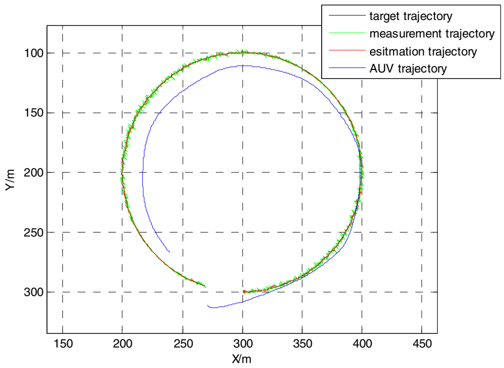

Fig. 4 Target tracking result

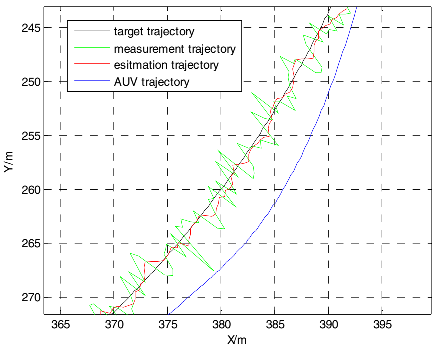

Fig. 5 Enlarged of Fig. 4

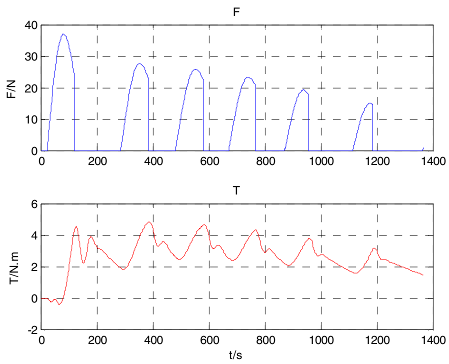

Fig. 6 Control force and yaw torque

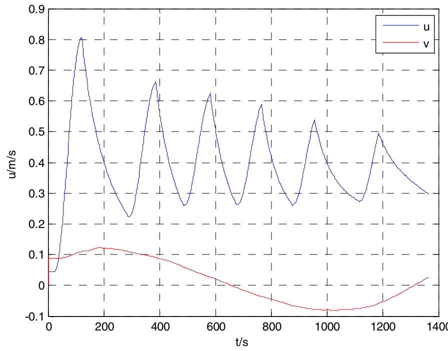

Fig. 7 Surge and sway of AUV

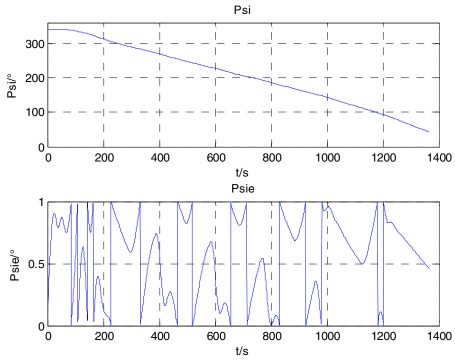

Fig. 8 Heading and heading error

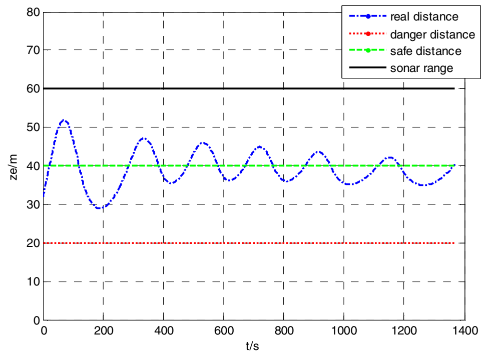

Fig.9 Distance between target and AUV

Fig.4 and Fig.5 show that UKF can estimate the position of the target and the observation noise is filtered, and AUV can track the target with the presence of constant current. Fig.6 shows the control force and torque which are computed by controllers and tracking strategy, when $Z_e < l_d$, $F = 0$; Fig.7 shows surge and sway. Fig.8 shows that absolute of heading error is less than 2°; Fig.9 shows that the tracking distance is between 30m and 50m which satisfy the demand.

VI. CONCLUSION

In this paper, UKF is applied to estimate the target movement state, PP guidance is introduced to compute the tracking error, heading and velocity controllers and tracking strategy are designed to make sure target tracking safe and effective. The results of the simulation experiment verify that the proposed methods are useful and effective.

ACKONLOGEMENT

This research work is supported by the National Natural Science Foundation of China (Grant No.E091002/50979017), Ph.D. Programs Foundation of Ministry of Education of China and Basic Technology (Grant No.20092304110008), Harbin Science and Technology Innovation Talents of Special Fund Project (Outstanding Subject Leaders) (No. 2012RFXXG083).

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