Improved LOS Guidance Law for Path Following of Underactuated USV with Sideslip Compensation

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Abstract— **In this paper, we present an improved line-of-sight guidance law (LOS) for path following of underactuated unmanned surface vehicles. In the proposed approach, the sideslip angle is treated as an unknown system state that is estimated simultaneously with the cross-track error using an augmented extended Kalman filter (AEKF). Simulation results demonstrate that the proposed guidance law exhibits faster convergence and better path following performance compared to the available LOS methods.**

Index Terms— **USV, Guidance, Path Following, Line-of-Sight (LOS), Predictor-based, Sideslip Compensation**

I. Introduction

Unmanned surface vehicles (USVs) have attracted significant interest in various fields of marine operations such as civilian harbor protection [1], environmental surveillance [2], reconnaissance [3], etc., due to their efficiency, lower operation costs and improved personnel safety [4]. In the marine operations where USVs are utilized, guidance system is of great importance. Guidance refers to the establishment of a desired path from the craft's current position to the selected target [5], [6]. As a typical motion control scenario, path following refers to following a predefined parameterized path, without temporal restrictions. Main objective in this motion scenario is to design a guidance law such that USV reaches and moves along a desired geometric path while assuring given dynamic specifications.

The line-of-sight (LOS) guidance is a commonly used principle for path following of marine vessels due to its simplicity and effectiveness. The LOS guidance method produces a desired yaw angle that acts as a control input for the heading controller. However, using the LOS guidance principle in its traditional form is not feasible when the vehicle is exposed to unknown drift forces caused by disturbances such as ocean current, waves and wind in the environment. Product of these disturbances is manifested in the occurrence of a deviation between USV's moving orientation and its heading, known as the sideslip, which increases the tracking error and thus negatively affects the overall performance [7].

If the sideslip angle is known, then its effects can be directly canceled out by a suitable modification of the guidance law. The sideslip angle can be measured with the use of optical correlation sensors, or calculated based on the measurements of velocities in surge and sway [8]. However, both of these approaches are either too expensive to implement or the required measurements are too noisy and therefore produce errors.

Alternatively, the sideslip can be compensated by using the integral LOS guidance law (ILOS), originally introduced in [9] and extensively analyzed in [10]. However, the ILOS can only compensate for the drift force without estimating the sideslip angle. A more effective method is an adaptive LOS method (ALOS) which directly estimates the value of the sideslip angle [11]. An improved ILOS for online estimation of the time-varying sideslip angle based on a reduced-order state observer is developed in [12]. The ILOS-based methods can only deal with a slowly varying sideslip and may exhibit large tracking errors and poor transient performance [13], [14]. To overcome these issues, the predictor-based methods have been proposed [14], [15]. In the predictor-based methods, the cross-track prediction errors are utilized to identify unknown sideslip angle with high accuracy and additional adjustable parameters are provided for smooth and fast estimation, see [14].

In this paper, we propose an improved LOS guidance law for path following of underactuated USVs with sideslip compensation. The sideslip angle is treated as an unknown system state that is estimated simultaneously with the cross-track error using an augmented extended Kalman filter (AEKF). This differs from the available predictor-based methods in which mutually independent adaptive gains are used to update the cross-track error and the sideslip angle. As a consequence, the proposed LOS method exhibits faster convergence speed and better path-following performance, which is demonstrated by numerical simulations.

The paper is organized as follows. Section II contains preliminaries and problem statement. In Section III, two commonly used guidance laws and the proposed guidance law are presented. Section IV contains simulation results, while Section V concludes the paper.

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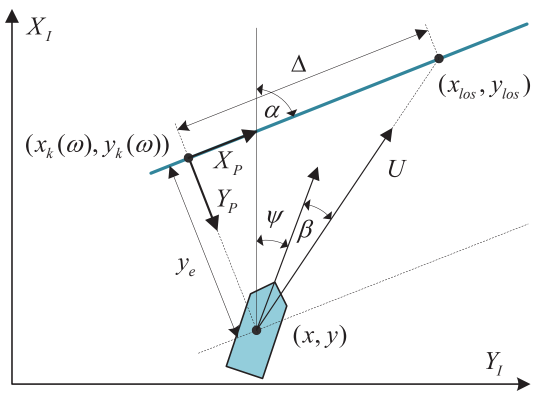

Fig. 1. LOS guidance geometry for 2-D path following.

II. Preliminaries and Problem Statement

There are three generally used reference frames for USV guidance in 2-D plane: earth-fixed inertial frame $\{I\}$, body-fixed frame $\{B\}$ and path-tangential reference frame $\{P\}$, as shown in Fig. 1. The look-ahead distance is denoted as Δ, and determines how far ahead the target location would be for the USV along the path. The look-ahead distance is a user-defined parameter and helps tune the convergence speed during the path following.

The kinematic model of an underactuated three-degree-of-freedom USV is expressed as follows [6]:

$$\begin{cases} \dot{x} = u\cos\psi - \upsilon\sin\psi, \\ \dot{y} = u\sin\psi + \upsilon\cos\psi, \\ \dot{\psi} = r, \end{cases} \tag{1}$$

where (x, y) is the position of the USV in an earth-fixed reference frame, u, υ, r represent surge, sway velocities and yaw rate, while ψ is the heading angle of the vehicle.

For the straight-line path following problem, the parameterized reference path is considered with path variable denoted by ω:

$$\begin{cases} x_k(\omega) = x_0 + \omega\cos\alpha, \\ y_k(\omega) = y_0 + \omega\sin\alpha, \end{cases} \tag{2}$$

where (x_0, y_0) is a fixed point on the path and $\alpha = \operatorname{atan2}({y_k}'(\omega), {x_k}'(\omega))$ denotes the path-tangential angle. This angle represents the rotation of $\{P\}$ reference frame from the $\{I\}$ reference frame and is constant $\alpha = \operatorname{atan2}(y_{j+1} - y_j, x_{j+1} - x_j)$ for the straight-line path following between the waypoints (x_j, y_j). The propagation of the path variable is given by

$$\dot{\omega} = \frac{U}{\sqrt{{x_k}'^2(\omega) + {y_k}'^2(\omega)}}, \tag{3}$$

where $U = \sqrt{u^2 + \upsilon^2}$ is the resultant speed of the USV [6].

The distance from the USV position (x, y) to the path, expressed in $\{P\}$ reference frame is

$$\begin{bmatrix} 0 \\ y_e \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix}^T \begin{bmatrix} x - x_k(\omega^*) \\ y - y_k(\omega^*) \end{bmatrix}, \tag{4}$$

where $(x_k(\omega^*), y_k(\omega^*))$ is the normal projection of (x, y) onto the path, and y_e is the cross-track error, i.e. orthogonal distance to the desired path.

System (4) can be expanded into

$$\begin{cases} 0 = (x - x_k(\omega^*))\cos\alpha + (y - y_k(\omega^*))\sin\alpha \\ y_e = -(x - x_k(\omega^*))\sin\alpha + (y - y_k(\omega^*))\cos\alpha. \end{cases} \tag{5}$$

Error dynamics is obtained by taking the time derivative of (5):

$$\dot{y}_e = U\sin(\psi - \alpha)\cos\beta + U\cos(\psi - \alpha)\sin\beta, \tag{6}$$

where $\beta = \operatorname{atan2}(\upsilon, u)$ is the sideslip angle expressed via surge and sway velocity.

The control objective in the path following motion scenario is to follow a predefined parameterized path without temporal constraints. This is achieved by applying the LOS guidance law to ensure that the velocity vector of the USV is directed towards the moving point (x_{los}, y_{los}) until the USV converges to the path, thus minimizing the cross-track error y_e (see Fig. 1) [7].

III. LOS Guidance Algorithms

In this section we present two commonly utilized LOS guidance laws which will be used for comparison. Furthermore, in Subsection III-C we present a novel LOS guidance law based on an augmented extended Kalman filter (AEKF), hereinafter referred to as KF-based LOS (KFLOS).

A. Adaptive LOS

By treating the sideslip angle β as a small constant parameter, the adaptive LOS (ALOS) guidance law of integral type is proposed in [11] as follows

$$\psi_d = \alpha + \arctan(-\frac{1}{\Delta}y_e - \hat{\beta}), \tag{7}$$

where $\hat{\beta}$ is an estimate of β and ψ_d is the desired heading angle. The adaptive law for $\hat{\beta}$ is designed as follows:

$$\dot{\hat{\beta}} = \frac{\gamma U \Delta}{\sqrt{\Delta^2 + (y_e + \Delta\hat{\beta})^2}} y_e, \tag{8}$$

where $\gamma > 0$ is an adaptive gain.

B. Predictor-based LOS

For the estimation of the unknown small constant sideslip angle, a state predictor LOS (PLOS) is proposed as [15]

$$\dot{\hat{y}}_e = U\sin(\psi - \alpha) + U\cos(\psi - \alpha)\hat{\beta} - k\tilde{y}_e, \tag{9}$$

where $\tilde{y}_e = \hat{y}_e - y_e$ and k is a positive constant. The update law for $\hat{\beta}$ based on the prediction error is designed as follows

$$\dot{\hat{\beta}} = -\Gamma U\cos(\psi - \alpha)\tilde{y}_e. \tag{10}$$

The desired heading angle is

$$\psi_d = \alpha - \arctan(\frac{1}{\Delta}y_e + \hat{\beta}). \tag{11}$$

C. KF-based LOS

Based on [16], from the definition of sideslip angle, where $v = u \tan\beta$, and the resultant speed U in combination with the model derived in (6), the path following error dynamic model can be rewritten as

$$\dot{y}_e = u \sin(\psi - \alpha) + u \cos(\psi - \alpha) \tan\beta. \qquad (12)$$

Let $\theta = \tan\beta$, then (12) can be rewritten as

$$\dot{y}_e = u \sin(\psi - \alpha) + u \cos(\psi - \alpha)\theta. \qquad (13)$$

A constant sideslip angle implies $\dot{\theta} = 0$. Define the augmented state vector as $\boldsymbol{\zeta} = \begin{bmatrix} y_e & \theta \end{bmatrix}^T$. Then, the dynamics of the augmented state vector can be written as $\dot{\boldsymbol{\zeta}} = \boldsymbol{f}(\boldsymbol{\zeta})$, where

$$\boldsymbol{f}(\boldsymbol{\zeta}) = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} = \begin{bmatrix} u \sin(\psi - \alpha) + u \cos(\psi - \alpha)\theta \\ 0 \end{bmatrix}.$$

Furthermore, define $\hat{\boldsymbol{\zeta}} = \begin{bmatrix} \hat{y}_e & \hat{\theta} \end{bmatrix}^T$ as the estimation of $\boldsymbol{\zeta}$. The goal is to design an estimator such that $\boldsymbol{\zeta} - \hat{\boldsymbol{\zeta}} \to 0$ as $t \to \infty$. .

In this paper we use the Augmented Extended Kalman filter (AEKF) to estimate $\boldsymbol{\zeta}$ [17]. The augmented state vector is predicted based on the system model and cross-track measurement

$$\dot{\hat{\boldsymbol{\zeta}}} = \boldsymbol{f}(\hat{\boldsymbol{\zeta}}) + \mathbf{K}(y_e - \hat{y}_e), \qquad (14)$$

where the time-varying Kalman gain $\mathbf{K}$ is updated as

$$\begin{matrix} \dot{\mathbf{P}} = \mathbf{AP} + \mathbf{PA}^T - \mathbf{KCP} + \mathbf{Q} \\ \mathbf{K} = \mathbf{PC}^T\mathbf{R}^{-1} \end{matrix}. \qquad (15)$$

Here, $\mathbf{P}$ represents the error covariance matrix, $\mathbf{Q}$ is the process covariance matrix, and $\mathbf{R}$ denotes the covariance of the measurement noise. It is well known that $\mathbf{K}$ is the optimal Kalman gain that minimizes the trace of the covariance matrix $\mathbf{P}$. Since we do not consider process and measurement noise in this paper, $\mathbf{Q}$ and $\mathbf{R}$ can be used to adjust the convergence speed of the estimator.

Matrices $\mathbf{A}$ and $\mathbf{C}$ are

$$\mathbf{A} = \begin{bmatrix} \frac{\partial f_1}{\partial y_e} & \frac{\partial f_1}{\partial \theta} \\ \frac{\partial f_2}{\partial y_e} & \frac{\partial f_2}{\partial \theta} \end{bmatrix}_{\boldsymbol{\zeta}(t) = \hat{\boldsymbol{\zeta}}(t)}, \quad \mathbf{C} = \begin{bmatrix} 1 & 0 \end{bmatrix}. \qquad (16)$$

Finally, the estimate of the sideslip angle is calculated as

$$\hat{\beta} = \arctan\hat{\theta}, \qquad (17)$$

on the bounded interval $[-\pi/2, \pi/2]$. In comparison to [11] and [15], there is no need for approximation for a small sideslip angle, thus making the proposed approach more applicable and precise. The desired heading angle is

$$\psi_d = \alpha - \arctan(\frac{1}{\Delta} y_e + \hat{\beta}). \qquad (18)$$

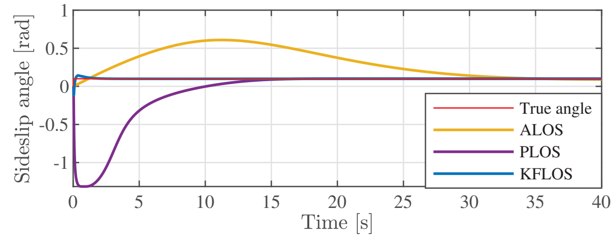

Fig. 2. S1: Sideslip angle estimation

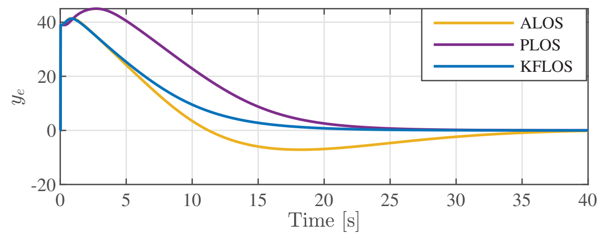

Fig. 3. S1: Cross-track error y_e

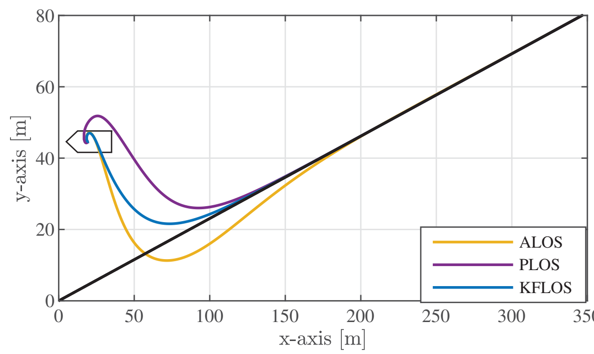

Fig. 4. S1: Path following performance

IV. Simulations

In this section, convergence properties of the proposed KF-based LOS guidance law are compared to those of ALOS and Predictor-based LOS. The USV yaw dynamics is chosen as a first-order Nomoto model with actuator dynamics:

$$\begin{cases} \dot{\psi} = r \\ \dot{r} = -\frac{1}{T} r + \frac{K}{T}\delta \end{cases}, \qquad (19)$$

where δ is the rudder angle of the USV. For controlling the yaw rate, a PD controller is used with the proportional gain $K_p = 0.6$ and differential gain $K_d = 0.35$. The USV parameters are $K = 20$ and $T = 1$.

Two straight-line path following scenarios, S_1 and S_2, are considered. Surge velocities for S_1 and S_2 are $u = 5m/s$ and $u = 3m/s$, respectively. The two scenarios also differ in an initial position and orientation of the USV. Sway velocity is $v = 0.5m/s$. In both scenarios, simulation parameters are selected as follows: $\Delta = 20m$, $\gamma = 0.001$, $k = 4$, $\Gamma = 0.1$, $\mathbf{R} = 0.1$ and the diagonal elements of the covariance matrix $\mathbf{Q}$ are set to 10.

Simulation results for the scenario S_1 are shown in Figs. 2, 3 and 4. From Fig. 2 it can be seen that with the use of KF-based LOS guidance, fast estimation of the sideslip

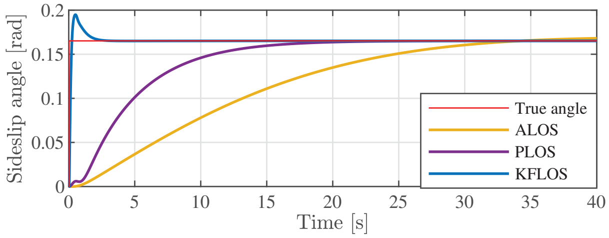

Fig. 5. S2: Sideslip angle estimation

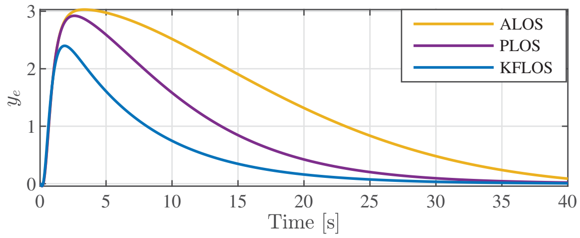

Fig. 6. S2: Cross-track error y_e

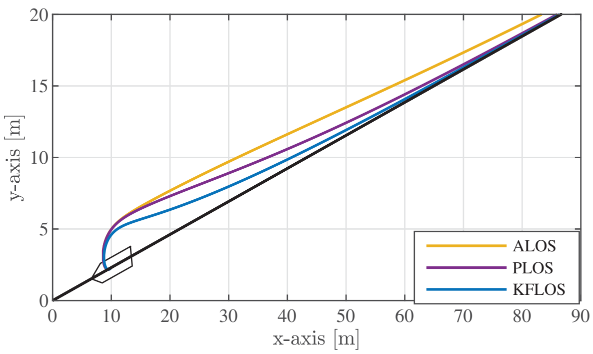

Fig. 7. S2: Path following performance

angle is achieved. Moreover, the convergence speed of the proposed estimator is significantly faster than ALOS and PLOS. As a consequence, the cross-track error has also the fastest convergence to zero, as can be seen from Fig. 3. Finally, in Fig. 4 it can be observed that the proposed LOS method ensures the fastest convergence of the actual USV path to the desired path.

The second scenario S_2, refers to the situation in which the vehicle is on the desired path but its bow is turned away from the desired direction of movement. Estimated sideslip angle, cross-track error and actual USV path are show in Figs. 5, 6 and 7, respectively. In this scenario, the KF-based LOS method estimates the actual sideslip angle significantly faster than the other two LOS methods. Also, the cross-track error converges to zero considerably faster.

V. Conclusion

This paper deals with the problem of designing a guidance law for the path following of underactuated USVs. A novel KF-based guidance law has been proposed, which allows the compensation of the sideslip angle caused by ocean currents. The proposed solution is not limited to small angles and exhibits faster estimation of the sideslip angle compared to other methods. Numerous simulations are carried out and the effectiveness of the proposed approach is demonstrated. In future work, the curved path-following problem will be considered.

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