Abstract—This paper considers the problem of standoff tracking control for unmanned aerial vehicle (UAV) where the UAV is used to track a moving target in unknown background wind. A new control approach combining the Lyapunov guidance vector field approach and a modified adaptive estimation strategy to estimate the velocities of unknown constant wind and unknown constant target motion is proposed. In the proposed approach, a variable heading rate controller based on the adaptive estimate is designed to achieve standoff tracking of moving target while the airspeed of the UAV can be specified to be constant. In addition, this proposed approach can be applied to perform standoff target tracking by using the UAV with an arbitrary initial heading. Finally, simulation results demonstrate the effectiveness of the proposed algorithm.

I. INTRODUCTION

In recent years, the research of unmanned aerial vehicles has received growing attention, as there are many potential applications in both military and civilian fields, such as surveillance[1]-[3], border patrol[4], search and rescue [5], convoy protection[6], etc.

This paper focuses on the problem of standoff tracking in which the UAV is used to fly a circular orbit around a moving target in unknown wind. In target tracking missions, the targets could be friendly, adversarial or unidentified. For the adversarial target tracking, the UAV must remain outside a critical threat range to reduce its exposure to the targets. For the friendly target tracking, due to the airspeed constraints, the UAV also must orbit around the target to maintain sensor contact. These applications above have spurred the development of standoff tracking approaches [6]-[13].

In [8], a path following approach called “good helmsman” is introduced to follow a standoff path. In this “good helmsman” path following approach, a Serret–Frenet formulation is used to represent the vehicle kinematics in terms of path parameters, and the controller is designed to bring the UAV from current path to the desired path by simultaneously regulating the cross track error and course angle error to zero in the Serret–Frenet frame. In addition, a linear observer for wind is constructed to reorient the desired path. Recently, a Lyapunov guidance vector field approach which stems from potential field work is introduced in [6] to guide the UAV to fly a circular orbit around a target. In [6], the Lyapunov guidance vector field is first designed for a stationary target in the absence of wind, and then a modified version of vector field is applied to the case with a moving target in known constant background wind. It is worth noting that in this Lyapunov guidance vector field approach, only variable heading rate control input is used to achieve standoff tracking with a constant commanded airspeed. However, the estimation approach for unknown target motion and wind is not taken into account in this paper.

Another vector field approach is proposed in [9] to generate desired course input and a sliding mode controller is used to bring the vehicle to follow the vector field so that the UAV achieves standoff tracking. This approach is robust to the unknown wind, but it may arouse high gain on the course rate controller to resist the unknown wind and this approach also does not consider the target motion. A similar vector field approach is also described in [10], and this approach uses heading rate control input exclusively to obtain the desired circular orbit while holding a constant airspeed. But the approach proposed in [10] falls short of giving a proof of global stability.

In practice, background wind is usually inevitable, and is commonly 20%~60% of the desired airspeed [9]. Meanwhile, the target motion also has to be considered, especially for the adversarial target tracking mission. Based on the Lyapunov guidance vector field introduced in [6], reference [13] proposes an adaptive estimation approach to estimate the velocities of unknown background wind and target motion using a variable airspeed controller under the assumption that the initial heading error is zero. This variable airspeed controller in [13] is also used to achieve angular spacing. However, it is probably not feasible to use the same control input (commanded airspeed) to achieve two different objectives in practical applications. Although the initial heading can be aligned with the desired heading by flying an initial loiter circle, there still exists heading error during the process of adaptive estimation.

Motivated by the work in [6] and [13], this paper aims to propose a control approach to achieve standoff tracking of moving target in unknown constant wind by using only the variable heading rate controller. In this proposed approach, an adaptive estimation strategy is introduced to estimate the velocities of unknown constant wind and unknown constant target motion. Based on the adaptive estimate and Lyapunov vector field, the variable heading rate controller is designed. The airspeed of the UAV is not utilized during this mission, so it can be specified to achieve some other aims. There are two potential advantages for this feature. First, it can maximize fuel efficiency when the UAV fly with a specified constant airspeed [10]. Second, it will be easy to realize coordinated standoff tracking since the UAVs can reach angular spacing by changing the airspeed [6]. Furthermore, this proposed approach can perform standoff tracking of moving target by using the UAV with an arbitrary initial
heading.

The remainder of this paper is organized as follows. Section II introduces the UAV dynamic model and Lyapunov guidance vector field approach. Based on Lyapunov guidance vector field, the algorithm of standoff tracking control of stationary target with no wind is described. Section III extends the standoff tracking controller to the case with moving target and unknown wind. A modified adaptive estimation strategy to estimate the velocities of the unknown constant wind and target motion is proposed. Afterwards, the stability of the adaptive estimation and tracking control is verified using LaSalle’s Invariance principle. In section IV, the performance of the proposed algorithm is illustrated via the simulation results. Finally, the conclusions are given in section V.

II. SYSTEM MODELING

In this section, the problem of standoff tracking of stationary target using a single UAV is described. First, a commonly used UAV model in the presence of background wind is presented. Then based on the work of [6], the Lyapunov guidance vector field approach is introduced to guide the UAV to track a stationary target in the absence of wind.

A. UAV Model

This paper considers the tracking control problem of a fixed wing UAV under the assumption that the altitude of the UAV is held constant. A kinematic model describing the relative motion of the UAV with respect to a moving target in the presence of wind is given by

\[
\begin{align*}
\dot{x}_r &= u_1 \cos \psi + W_x - \dot{x}_t \\
\dot{y}_r &= u_1 \sin \psi + W_y - \dot{y}_t \\
\psi &= u_2
\end{align*}
\]

(1)

where \((x_r, y_r) \in \mathbb{R}^2\) is the two-dimensional position of the aircraft in the target frame, \(\psi \in [-\pi, \pi]\) is the heading angle, \((x_t, y_t) \in \mathbb{R}^2\) is the constant velocity of target, \((W_x, W_y) \in \mathbb{R}^2\) is the steady wind velocity (see Fig. 1) and \(u_1, u_2\) are the two control input signals which are airspeed input and heading rate input respectively. Due to the stall guide the UAV to track a stationary target in the absence of wind.

B. Lyapunov Vector Field

Lyapunov guidance vector field is utilized to generate airspeed and heading rate control inputs which guide the UAV to circle about a designated ground target with a desired standoff radius \(r_d\). In this section, for the sake of simplicity, we assume that the ground target is stationary and centered at the origin of the inertial frame, i.e. \(x_t = x = 0\) and \(y_t = y\), and there is no wind. Consider the following Lyapunov function candidate

\[ V(x, y) = (r^2 - r_d^2)^2 \]

(4)

where \(r = (x^2 + y^2)^{1/2}\) is the horizontal distance between the UAV and the target. In order to follow the circular orbit, the desired velocity of UAV \(\dot{x} = \dot{x}_d\) and \(\dot{y} = \dot{y}_d\) is chosen according to the guidance vector field \(f(x, y)\) given by

\[
\begin{align*}
\dot{x}_d &= \frac{1}{r} \left( y \frac{r^2 - r_d^2}{r^2 + r_d^2} + \frac{2rr_d}{r^2 + r_d^2} \right) \\
\dot{y}_d &= -\frac{1}{r} \left( x \frac{r^2 - r_d^2}{r^2 + r_d^2} - \frac{2rr_d}{r^2 + r_d^2} \right)
\end{align*}
\]

(5)

where \(v_0\) is the constant nominal airspeed which can be prespecified, and \(\alpha(t)\) is a positive variable scaling factor. By adjusting the variable scaling factor \(\alpha(t)\) properly, the commanded airspeed of the UAV \(u_1\) can be equal to the nominal airspeed \(v_0\). This vector field can also be represented in polar coordinates as follows.

\[
g(r, \theta) = \begin{bmatrix} \dot{r} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \dot{r} \cos \theta + \dot{y} \sin \theta \\ -\dot{r} \sin \theta + \dot{x} \cos \theta \end{bmatrix} = \alpha(t) v_0 \begin{bmatrix} \frac{r^2 - r_d^2}{r^2 + r_d^2} \\ \frac{2rr_d}{r^2 + r_d^2} \end{bmatrix}
\]

(6)

where \(\theta\) is the clock angle clarified in Fig. 1, and \(x = r \cos \theta\), \(y = r \sin \theta\). To simplify the analysis, an additional notation \(\phi\) is introduced, which is defined as follows.

\[
\cos \phi = \frac{r^2 - r_d^2}{r^2 + r_d^2}, \quad \sin \phi = \frac{2rr_d}{r^2 + r_d^2}
\]

(7)

From (7), it can be observed that \(\phi \in [0, \pi]\), and
\[ \phi \to 0 \text{ as } r \to \infty, \ \phi = \pi/2 \text{ when } r = r_a, \text{ and } \phi \to \pi \text{ as } r \to 0 \ [13]. \]

Then vector field (5) and (6) can be rewritten respectively as

\[
\begin{bmatrix}
\dot{x}_d \\
\dot{y}_d
\end{bmatrix} = -\alpha(t)v_0 \begin{bmatrix}
\cos(\theta - \phi) \\
\sin(\theta - \phi)
\end{bmatrix}
\]

(8)

\[
g(r, \theta) = \begin{bmatrix}
\dot{r} \\
r\dot{\theta}
\end{bmatrix} = \begin{bmatrix}
-\alpha(t)v_0 \cos \phi \\
\alpha(t)v_0 \sin \phi
\end{bmatrix}
\]

(9)

The time derivative of Lyapunov function (4) can be calculated using the desired velocity based on the vector field.

\[ \dot{V} = -4\alpha(t)v_0 r \frac{(r^2 - r_a^2)^2}{r^3 + r_a^2} \leq 0 \]  

(10)

By LaSalle’s Invariance principle, \( r \) converges to the desired standoff radius \( r_a \) asymptotically. In order to travel along the vector field, the heading of the UAV should follow the desired heading which is calculated from (5) via

\[ \psi_d = \arctan \left( \frac{y(r^2 - r_a^2) - x2rr_a}{x(r^2 - r_a^2) - y2rr_a} \right) \]

(11)

The desired heading rate can be obtained by taking the time derivative of (11).

\[ \dot{\psi}_d = 4\alpha(t)v_0 \frac{r_a^3}{(r^3 + r_a^2)^2} \]  

(12)

III. STANDOFF TRACKING WITH ADAPTIVE ESTIMATION

In this section, the Lyapunov vector field approach introduced in the previous section is extended to the case with target motion and unknown wind. In this paper, we assume that the target velocity and the wind velocity are constant. Motivated by the work in [13], a modified adaptive estimator is utilized to estimate the unknown constant moving target velocity using only the variable heading rate controller. This approach is also suitable for the case with an arbitrary initial heading. The system architecture is illustrated in Fig.2. First step, the adaptive estimator makes use of the actual outputs (heading angle \( \psi \), relative radius \( r \) and clock angle \( \theta \)) to estimate the moving target velocity. Second step, based on the estimate of the moving target velocity, the Lyapunov vector field generates a desired heading. Third step, the heading tracking controller generates the heading rate control input to the UAV. Then the UAV implements the heading rate control to track the desired heading.

![Fig.2. System architecture with an adaptive estimator for the unknown moving target velocity.](image)

The UAV kinematic model (3) is used in this section with unknown constant moving target velocity \([T_x, T_y]\). Generally, the Lyapunov vector field approach is applicable to the case in which the moving target velocity is smaller than the nominal airspeed. Therefore, we assume that \( T_x \) and \( T_y \) are constant and there exists an upper bound \( T^* \) such that \( |T_x| \leq T^*, |T_y| \leq T^* \). \([\hat{T}_x, \hat{T}_y]\) is introduced to denote the estimate of \([T_x, T_y]\), and the actual moving target velocity and its estimate are defined as follows [13].

\[ T_x = T^* \tanh \phi_x^*, T_y = T^* \tanh \phi_y^* \]

(13)

\[ \hat{T}_x = T^* \tanh \hat{\phi}_x, \hat{T}_y = T^* \tanh \hat{\phi}_y \]

where, \( \phi_x^*, \phi_y^* \) are unknown constants, and \( \hat{\phi}_x, \hat{\phi}_y \) are the corresponding estimates which can be used to bound the estimate of the moving target velocity.

Construct the following desired velocity of the UAV

\[ u_1 \cos \psi = -\alpha(t)v_0 \cos(\theta - \phi) + \hat{T}_x \]

(14)

\[ u_1 \sin \psi = -\alpha(t)v_0 \sin(\theta - \phi) + \hat{T}_y \]

where all the variables have the same meaning as before. The variable scaling factor \( \alpha(t) \) here is used to keep the airspeed control input \( u_1 \) constant and equal to \( v_0 \) via the following calculation.

\[ u_1^2 = (-\alpha(t)v_0 \cos(\theta - \phi) + \hat{T}_x)^2 + (-\alpha(t)v_0 \sin(\theta - \phi) + \hat{T}_y)^2 \]  

(15)

Let \( u_1 = v_0 \), and \( \alpha(t) \) can be obtained as follows.

\[ \alpha(t) = \frac{1}{v_0^2} \left( \hat{T}_x \cos(\theta - \phi) + \hat{T}_y \sin(\theta - \phi) \right) \]

(16)

\[ + \left[ \frac{1}{v_0^2} \left( \hat{T}_x \cos(\theta - \phi) + \hat{T}_y \sin(\theta - \phi) \right)^2 + (v_0^2 - \hat{T}_x^2 - \hat{T}_y^2) \right]^{1/2} \]

From (16), it can be observed that, provided the nominal airspeed \( v_0 \) is larger than the estimate of the moving target velocity, \( \alpha(t) \) can always be positive.

The desired heading of the UAV can also be obtained from (14) via

\[ \psi_d = \arctan \left( \frac{-\alpha(t)v_0 \sin(\theta - \phi) + \hat{T}_y}{-\alpha(t)v_0 \cos(\theta - \phi) + \hat{T}_x} \right) \]

(17)

The corresponding desired heading rate can be obtained by differentiating (17).

For the UAV with arbitrary heading \( \psi \), the heading error can be defined by

\[ \psi_e = \psi - \psi_d \in [-\pi, +\pi] \]

(18)

According to the definition of the heading error, the actual airspeed can be obtained by

\[
\begin{bmatrix}
u_1 \cos \psi_e \\
u_1 \sin \psi_e
\end{bmatrix} = \begin{bmatrix}
\cos \psi_e & -\sin \psi_e \\
\sin \psi_e & \cos \psi_e
\end{bmatrix} \begin{bmatrix}
u_1 \cos \psi_d \\
u_1 \sin \psi_d
\end{bmatrix}
\]

(19)

Then, the actual UAV kinematic model with the adaptive estimation is as follows.

\[
\begin{bmatrix}
\dot{x}_e \\
\dot{y}_e
\end{bmatrix} = \begin{bmatrix}
\cos \psi_e & -\sin \psi_e \\
\sin \psi_e & \cos \psi_e
\end{bmatrix} \begin{bmatrix}
u_1 \cos \psi_d \\
u_1 \sin \psi_d
\end{bmatrix} - \begin{bmatrix}
T_x \\
T_y
\end{bmatrix}
\]

(20)

This kinematic model (20) can be expressed in polar.
coordinates as follows.
\[
\begin{bmatrix}
\dot{r} \\
\dot{\theta}
\end{bmatrix} = \begin{bmatrix}
x, \cos \theta + \dot{y}, \sin \theta \\
-\dot{x}, \sin \theta + \dot{y}, \cos \theta
\end{bmatrix}
\]
\[
\begin{bmatrix}
\dot{r} \\
\dot{\theta}
\end{bmatrix} = \begin{bmatrix}
-\alpha(t)v_0 \cos(\theta - \psi_e) + \dot{T}_1 \cos(\theta - \psi_e) + \dot{T}_1 \cos(\theta - \psi_e) + \sin(\theta - \psi_e) - \dot{T}_1 \cos(\theta - \psi_e) - \sin(\theta - \psi_e)
\end{bmatrix}
\]
\[
\begin{bmatrix}
\dot{r} \\
\dot{\theta}
\end{bmatrix} = \begin{bmatrix}
-\alpha(t)v_0 \sin(\theta - \psi_e) - \dot{T}_1 \sin(\theta - \psi_e) + \dot{T}_1 \sin(\theta - \psi_e) + \cos(\theta - \psi_e) + \sin(\theta - \psi_e)
\end{bmatrix}
\]

where \( \dot{T}_1 = \dot{T}_1 - T_1 \), \( \dot{T}_2 = \dot{T}_2 - T_2 \) are the estimation errors of the moving target velocity and
\[
\Delta t = 2 \left( \alpha(t)v_0 \sin \left( \frac{20 - \psi_e}{2} \right) - \dot{T}_1 \sin \left( \frac{20 - \psi_e}{2} \right) + \dot{T}_1 \cos \left( \frac{20 - \psi_e}{2} \right) \right)
\]
\[
\Delta \dot{\theta} = 2 \left( \alpha(t)v_0 \cos \left( \frac{20 - \psi_e}{2} \right) - \dot{T}_1 \cos \left( \frac{20 - \psi_e}{2} \right) - \dot{T}_1 \sin \left( \frac{20 - \psi_e}{2} \right) \right)
\]

In [13], a perfect relative motion based on the Lyapunov guidance vector field is defined. The adaptive estimation approach proposed in [13] is carried out by tracking the perfect trajectory generated by the perfect relative motion with respect to the moving target. In this paper, the perfect relative motion is still used to generate the perfect trajectory, but instead of tracking the trajectory, this modified adaptive estimation is achieved by tracking the radius which is the horizontal distance between the moving target and the perfect model. The perfect relative motion is defined as follows.

\[
\begin{bmatrix}
\dot{r} \\
\dot{\theta}
\end{bmatrix} = \begin{bmatrix}
\alpha(t)v_0 \\
\dot{r} \dot{\theta}
\end{bmatrix} = \begin{bmatrix}
\alpha(t)v_0 - \dot{T}_1 \cos(\theta - \psi_e) - \dot{T}_1 \sin(\theta - \psi_e) + \dot{T}_1 \sin(\theta - \psi_e)
\end{bmatrix}
\]

The term \( M \) is a positive constant to guarantee positive definiteness of the Lyapunov function, and \( \mu > 0, \lambda > 0 \).

The corresponding time derivative of the Lyapunov function \( V \) is given by
\[
V = e_\theta \dot{e}_\theta + \mu T^+ \left( \dot{\phi}_e - \dot{\phi}, \tan \phi_e' \right) + \mu T^+ \left( \dot{\phi}_e - \dot{\phi}, \tan \phi_e' + \lambda \psi_e \sin \left( \frac{\psi_e}{2} \right) \right)
\]

To specify the time derivative of the Lyapunov function to be nonpositive, the update law of the adaptive estimation and the commanded heading rate are given by the following equations.
\[
\dot{\phi}_e = -e_\theta \cos \theta, \quad \dot{\phi}_e = -e_\theta \sin \theta
\]

\[
\psi_e = -\frac{e_\theta}{\lambda} - k \psi_e \Rightarrow \psi_e = -\frac{e_\theta}{\lambda} - k \psi_e + \psi_e_d
\]

By substituting (28) into (27), the time derivative of \( V \) is obtained.
\[
\dot{V} = -e_\theta \dot{e}_\theta \left( \frac{r_e^2}{r_p^2} \right) + \dot{\phi}_e \cos \theta + e_\theta \dot{\phi}_e + e_\theta \dot{\phi}_e \sin \psi_e - k \lambda \sin \left( \frac{\psi_e}{2} \right) \psi_e
\]

\[
= -e_\theta \dot{e}_\theta \left( \frac{r_e^2}{r_p^2} \right) + \dot{\phi}_e \cos \theta - e_\theta \dot{\phi}_e + e_\theta \dot{\phi}_e \sin \psi_e - k \lambda \sin \left( \frac{\psi_e}{2} \right) \psi_e \leq 0
\]

The value of the term \( M \) needs to be determined ahead of the convergence analysis. Consider the following function \( f(x) \) with respect to \( x \)
\[
f(x) = \log \cosh x - x \tanh x_0
\]

\[
df(x) = \frac{\tanh x - \tanh x_0}{dx}
\]

with \( x_0 \) : an arbitrary constant

Observe from (30) and (31) that, when \( x = x_0 \), \( f(x) \) reaches the minimum. So the second and third terms in equation (26) have minimum values, when \( \dot{\phi}_e = \phi_e', \phi = \phi_e' \).

Now the value of \( M \) can be determined by
\[
M = \mu T^+ \left[ \log \cosh \phi_e - \phi_e', \tan \phi_e' \right] + \log \cosh \phi_e - \phi_e', \tan \phi_e'
\]

\[
\leq 2 \mu T^+ \log 2
\]

which can guarantee positive definiteness of \( V \).

In this approach, the radius error \( e_r \) is initially equal to zero, and the initial value of \( \dot{\phi}_e, \dot{\phi}_e \) can also be set to be zero. Then, the radius error \( e_r \) during the adaptive estimation procedure can be bounded by
\[
\frac{1}{2} \dot{e}_r^2 \leq V \leq V(0) = M + 4 \lambda \sin^2 \left( \frac{\psi_e}{4} \right)
\]

From (33), note that, the initial heading error of the UAV directly affects the upper bound of the radius error \( e_r \).

Now, we proceed to analyze the stability of this proposed approach. From (29) it can be observed that
\( \dot{V} = 0 \) implies \( e_r = 0 \) and \( \psi_e = 0 \). By LaSalle’s Invariance principle, it follows that \( r \to r_p \) and \( \psi \to \psi_d \), asymptotically as \( t \to \infty \). Here, \( r_p \) will converge to \( r_d \) in finite time in terms of the dynamics of the perfect model, which implies that \( r \to r_p \) as \( t \to \infty \).

It is worth noting that, in this approach, the proposed Lyapunov function does not include the clock angle \( \theta \) of the UAV. So the clock angle error between the actual UAV and the perfect model may not converge to zero. In addition, the performance of the adaptive estimate for moving target velocity depends on the dynamics of the first two equations of (28). \( e_r = 0 \) implies \( \dot{\phi}_r = 0 \) and \( \dot{\phi}_\psi = 0 \), which in turn implies that the adaptive estimate converges to a constant velocity.

Due to the roll angle constraint of the fixed wing UAV, the commanded heading rate must not exceed the maximum heading rate. According to (28), the heading rate is \( \dot{\psi} = -e_r \Delta \cdot \lambda - k e_\psi + \psi_d \). Here, \( \lambda \) should be chosen to be large enough to assure the effectiveness of the heading rate input, i.e. \( |\dot{\psi}| \leq \omega_{\text{max}} \).

### IV. Simulation Results

In this section, we simulate two scenarios using the proposed approach. In the first scenario, the UAV starts without initial heading error, i.e. \( \psi_{\text{o}} = 0 \), and performs standoff tracking of moving target in unknown constant background wind. In the second scenario, the UAV performs the same mission with initial heading error \( \psi_{\text{o}} = 2.8476 \text{rad} \). Simulation results are illustrated to demonstrate the validity of the proposed approach. Table I shows the specifications of the UAV and control law parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal airspeed ( v_0 )</td>
<td>20 m/s</td>
</tr>
<tr>
<td>Maximum heading rate ( \omega_{\text{max}} )</td>
<td>0.2 rad/s</td>
</tr>
<tr>
<td>Standoff radius ( \rho )</td>
<td>300 m</td>
</tr>
<tr>
<td>Control law parameter ( \lambda )</td>
<td>2000</td>
</tr>
<tr>
<td>Estimation update law parameter ( \mu )</td>
<td>400</td>
</tr>
<tr>
<td>Heading feedback gain ( k )</td>
<td>0.5</td>
</tr>
<tr>
<td>Moving target velocity ([T_x, T_y])</td>
<td>([8 \text{ m/s}, -6 \text{ m/s}])</td>
</tr>
<tr>
<td>Upper bound ( T^* )</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Initial position ([x_0, y_0])</td>
<td>([800 \text{ m}, 800 \text{ m}])</td>
</tr>
</tbody>
</table>

Fig. 3, Fig. 4 and Fig. 5 describe the first scenario. Fig. 3 shows the trajectory of the UAV with respect to the moving target frame. Although there exist unknown target motion and background wind, the trajectory still can converge the circular orbit with radius \( r_p \). Fig. 4 shows the adaptive estimate of moving target velocity. As seen from this figure that the adaptive estimate \([\hat{T}_x, \hat{T}_y]\) is initially set to be zero, and then it converges to the actual value \([8 \text{ m/s}, -6 \text{ m/s}]\). Fig. 5 shows the commanded heading rate of the UAV, where it can be observed that the commanded heading rate varies periodically after the adaptive estimate converges to the actual value. Furthermore, the commanded heading rate is always smaller than the specified maximum heading rate.

In order to analyze to the effect of the initial heading error, the second scenario is simulated. Fig. 6 shows the trajectory of the UAV with initial heading error \( \psi_{\text{o}} = 2.8476 \text{rad} \). Compared with Fig. 4, Fig. 7 shows that, due to the large initial heading error, it takes longer time to make the adaptive estimate converge to the actual moving target velocity. Fig. 8 shows that the commanded heading rate reaches saturation at the beginning since the controller needs to regulate the large
heading error to zero by using maximum heading rate.

![Diagram](image)

Fig.6. Standoff tracking of moving target in unknown wind ($\psi_e = 2.8476$).

![Diagram](image)

Fig.7. Adaptive estimate of the moving target velocity ($\psi_e = 2.8476$).

![Diagram](image)

Fig.8. Commanded heading rate ($\psi_e = 2.8476$).

V. CONCLUSIONS

In this paper, a modified adaptive estimation strategy is proposed to estimate the velocities of the unknown wind and target motion. Based on the adaptive estimate, the proposed approach uses only the variable heading rate controller to achieve standoff tracking while the airspeed of the UAV can be specified for other aims. In addition, the proposed approach can be applied to the case that the UAV has an arbitrary initial heading. Simulation results demonstrate the effectiveness of the proposed approach.

REFERENCES


