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ROBUST OUTPUT TRACKING CONTROL OF VTOL AIRCRAFT BASED ON IMMERSION AND MANIFOLD INVARIANCE

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Abstract. *This paper presents a robust output tracking control strategy to force an input-disturbed non-minimum phase vertical take-off and landing (VTOL) aircraft to asymptotically track a given reference trajectory. To attenuate the effects of input disturbances, an adaptive system immersion and manifold invariance (I&I) disturbance estimator is developed. The design of disturbance estimator separates from the controller, which makes the resulting modular adaptive controllers easier to tune compared to classical adaptive control method. By employing two global coordinate transformations, the tracking problem of the VTOL aircraft is converted to the stabilizing problem of two error subsystems. Then based on the adaptive I&I disturbance estimators, we propose two low-dimensional controllers separately to stabilize the decomposed subsystems, and make the overall closed-loop system exponentially stable. Numerical simulation results and stability analysis demonstrate the effectiveness and robustness of the proposed control method.*
Keywords: Output tracking, VTOL aircraft, Immersion and invariance, Input disturbances

1. **Introduction.** Over the past few years, the control problem of VTOL aircraft has attracted much attention from control community due to its broad applications and theoretic difficulties [1]. The main difficulty of VTOL aircraft control is that it is non-minimum phase and underactuated [2-5]. The existing work with respect to VTOL aircraft control can be divided into two main branches: the stabilization control and the trajectory tracking control. Recently, numerous control methods have been proposed. In [6,7], the input coupling was ignored and the approximate input-output linearization method was applied to stabilizing the unstable zero dynamics. On the other hand, in [8] the original system was decomposed into the minimum and non-minimum phase parts, and then the two controllers are designed respectively to control the corresponding subsystem. In particular, a nonlinear observer was designed and a backstepping technique was applied to achieving global output tracking of a VTOL aircraft in [9,10]. [11] offered a new method for achieving global stability in a VTOL aircraft with bounded thrust input. It should be pointed that all of aforementioned works ignore the effects of input-dependent disturbance uncertainties. Actually, there exist the uncertainties such as inaccurate torques of the control motors, the bias of center of gravity and the ground effects. If not dealt with properly, they may produce a significant degradation in the tracking performance or even lead to loss stability. In the case of [12], a robust output tracking control scheme for a VTOL aircraft was established in the presence of input disturbances, but the design process was very complex and difficult to realize. Moreover, the similar results are few.

To deal with this problem, we develop a robust adaptive output tracking control strategy to force a VTOL aircraft in the presence of input disturbances. The method is based on an adaptive I&I (system immersion and manifold invariance) approach [13-15], which can guarantee that the disturbance's estimation converges to its true value. Because the I&I approach allows the prescribed asymptotically stable dynamics to be assigned to the estimation error, the resulting modular adaptive controller is easier to tune compared to classical adaptive control method. So, it is suitable to compensate and estimate the input disturbances online.

The remainder of this paper is organized as follows. The system dynamics of the VTOL aircraft and decoupling transformation are formulated in Section 2. In Section 3, we present the adaptive I&I estimation law. The robust control strategy is given in Section 4. The validity of the proposed control strategy is illustrated via simulation results in Section 5. Finally, conclusions are drawn in Section 6.

2. **Problem Statement and Preliminaries.** According to [6], the nominal mathematical model of the VTOL aircraft moving in vertical-lateral plane is described as

$$\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= -(u_1 + \xi_1(t))\sin x_5 + \varepsilon(u_2 + \xi_2(t))\cos x_5 \\
\dot{x}_3 &= x_4 \\
\dot{x}_4 &= (u_1 + \xi_1(t))\cos x_5 + \varepsilon(u_2 + \xi_2(t))\sin x_5 - g \\
\dot{x}_5 &= x_6 \\
\dot{x}_6 &= u_2 + \xi_2(t)
\end{aligned} \tag{1}$$

where x_1, x_3, and x_5 denote respectively the position of the aircraft center of mass and roll angle, and x_2, x_4, and x_6 denote linear and roll angular velocities of the aircraft, and u_1 and u_2 are the thrust and the rolling moment, respectively; $g > 0$ is the gravitational acceleration, and ε is a small constant coupling between the roll moment and the lateral force; $\xi_1(t)$ and $\xi_2(t)$ are the thrust and rolling moment disturbances, which are matched with the inputs. The outputs of the controlled plant are $y_1 = x_1$, $y_2 = x_3$ and $y_3 = x_5$.

By setting $x_1 = x_2 = x_3 = x_4 = 0$ and without considering $\xi_1(t)$ and $\xi_2(t)$, it can be obtained that

$$\ddot{x}_5 = \frac{1}{\varepsilon}\sin x_5$$

that is, the zero dynamics of the aircraft model (1) is asymptotically unstable for $\varepsilon \neq 0$ which means that the VTOL aircraft is non-minimum phase [6].

For system (1) we assume that input disturbances $\xi_1(t)$ and $\xi_2(t)$ are bounded and derivable, and their derivatives are also bounded.

Define $d_1(t) = -\xi_1(t)\sin x_5 + \varepsilon\xi_2(t)\cos x_5$, $d_2(t) = \xi_1(t)\cos x_5 + \varepsilon\xi_2(t)\sin x_5$, $d_3(t) = \xi_2(t)$, and system (1) becomes

$$\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= -u_1\sin x_5 + \varepsilon u_2\cos x_5 + d_1(t) \\
\dot{x}_3 &= x_4 \\
\dot{x}_4 &= u_1\cos x_5 + \varepsilon u_2\sin x_5 - g + d_2(t) \\
\dot{x}_5 &= x_6 \\
\dot{x}_6 &= u_2 + d_3(t)
\end{aligned} \tag{2}$$

In this paper, the control objective is to design a robust control law so that the output y_1 and y_2 can asymptotically track the given reference trajectories y_{1d} and y_{2d}, respectively, while keeping the internal dynamics (x_5, x_6) stable.

2.1. **Coordinate transformations.** In order to make u_1 and u_2 not appear in internal dynamics, we use the input coordinate transformation for Equation (2) to obtain

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= w_1 + d_1(t) \\ \dot{x}_3 &= x_4 \\ \dot{x}_4 &= w_2 + d_2(t) \\ \dot{x}_5 &= x_6 \\ \dot{x}_6 &= \frac{1}{\varepsilon} w_1 \cos x_5 + \frac{1}{\varepsilon} w_2 \sin x_5 + \frac{g}{\varepsilon} \sin x_5 + d_3(t) \end{aligned} \tag{3}$$

where w_1 and w_2 are new inputs defined by the locally invertible feedback transformation

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} -\sin x_5 & \varepsilon \cos x_5 \\ \cos x_5 & \varepsilon \sin x_5 \end{bmatrix}^{-1} \begin{bmatrix} w_1 \\ w_2 + g \end{bmatrix} \tag{4}$$

2.2. **System decomposition.** To solve the tracking problem, we utilize a decomposition approach described in [8]. Introducing the following coordinate transformations

$$\begin{aligned} &e_1 = x_1 - y_{1d}, \quad e_2 = x_2 - \dot{y}_{1d}, \quad e_3 = x_3 - y_{2d}, \quad e_4 = x_4 - \dot{y}_{2d} \\ &v_1 = w_1 - \ddot{y}_{d1}, \quad v_2 = w_2 - \ddot{y}_{d2}, \quad \eta_1 = x_5, \quad \eta_2 = \varepsilon x_6 - e_2 \cos x_5 - e_4 \sin x_5 \end{aligned} \tag{5}$$

therefore, the tracking error system becomes

$$\begin{aligned} \dot{e}_1 &= e_2 \\ \dot{e}_2 &= v_1 + d_1(t) \\ \dot{e}_3 &= e_4 \\ \dot{e}_4 &= v_2 + d_2(t) \\ \dot{\eta}_1 &= \frac{1}{\varepsilon}(\eta_2 + e_2 \cos \eta_1 + e_4 \sin \eta_1) \\ \dot{\eta}_2 &= \frac{1}{\varepsilon}(\eta_2 + e_2 \cos \eta_1 + e_4 \sin \eta_1)(e_2 \sin \eta_1 - e_4 \cos \eta_1) + \ddot{y}_{d1} \cos \eta_1 + (\ddot{y}_{d2} + g) \sin \eta_1 \end{aligned} \tag{6}$$

where v_1 and v_2 will be designed in the following.

The unstable zero dynamics of tracking error system (6) can be written as

$$\dot{\eta} = \Gamma\left(\eta, e, \ddot{Y}_d\right) \tag{7}$$

where $\eta = (\eta_1, \eta_2)^T$, $e = (e_1, e_2, e_3, e_4)^T$, and $\ddot{Y}_d = (\ddot{y}_{d1}, \ddot{y}_{d2})^T$.

Because of

$$\left.\frac{\partial \Gamma\left(\eta, e, \ddot{Y}_d\right)}{\partial(e_1, e_2)}\right|_O \neq \boldsymbol{O}_{2\times 2}, \quad \left.\frac{\partial \Gamma\left(\eta, e, \ddot{Y}_d\right)}{\partial(e_3, e_4)}\right|_O = \boldsymbol{O}_{2\times 2} \tag{8}$$

system (6) can be divided into the following two parts, that is, a minimum phase part for control of vertical flight dynamics:

$$\begin{aligned} \dot{e}_3 &= e_4 \\ \dot{e}_4 &= v_2 + d_2(t) \end{aligned} \tag{9}$$

and a non-minimum phase part for control of the coupled horizontal and roll flight dynamics:

$$\begin{aligned} \dot{e}_1 &= e_2 \\ \dot{e}_2 &= v_1 + d_1(t) \\ \dot{\eta} &= \Gamma\left(\eta, e, \ddot{Y}_d\right) \end{aligned} \tag{10}$$

Up to now, the tracking problem of original system (2) is transformed into the stabilization problem for error subsystems. On the basis of above decomposing, we can design the controllers for two subsystems, separately.

3. **Adaptive I&I Disturbance Estimator.** In this subsection, two adaptive I&I disturbance estimators will be designed to compensate the input disturbances. According to adaptive I&I principle, we construct the disturbance estimation laws as follows.

Let disturbance estimation errors be

$$z_1(t) = \hat{d}_1(t) + \beta_1(e_1, e_2) - d_1(t) \tag{11}$$

$$z_2(t) = \hat{d}_2(t) + \beta_2(e_3, e_4) - d_2(t) \tag{12}$$

where $\hat{d}_i(t)$ is the disturbance estimation of $d_i(t)$, and $\beta_i(\cdot)$ is a smooth function to specify latter, $i = 1, 2$.

Differentiating (11) and (12) with regard to time yields

$$\dot{z}_1 = \dot{\hat{d}}_1 + \frac{\partial \beta_1}{\partial e_1} e_2 + \frac{\partial \beta_1}{\partial e_2}(v_1 + d_1(t)) = \dot{\hat{d}}_1 + \frac{\partial \beta_1}{\partial e_1} e_2 + \frac{\partial \beta_1}{\partial e_2}\left(v_1 + \hat{d}_1(t) + \beta_1 - z_1\right) \tag{13}$$

$$\dot{z}_2 = \dot{\hat{d}}_2 + \frac{\partial \beta_2}{\partial e_3} e_4 + \frac{\partial \beta_2}{\partial e_4}(v_2 + d_2(t)) = \dot{\hat{d}}_2 + \frac{\partial \beta_3}{\partial e_3} e_4 + \frac{\partial \beta_2}{\partial e_4}\left(v_2 + \hat{d}_2(t) + \beta_2 - z_2\right) \tag{14}$$

Noticing (13) and (14), we can design adaptive estimation laws

$$\dot{\hat{d}}_1 = -\frac{\partial \beta_1}{\partial e_1} e_2 - \frac{\partial \beta_1}{\partial e_2}\left(v_1 + \hat{d}_1(t) + \beta_1\right) \tag{15}$$

$$\dot{\hat{d}}_2 = -\frac{\partial \beta_2}{\partial e_3} e_4 - \frac{\partial \beta_2}{\partial e_4}\left(v_2 + \hat{d}_2(t) + \beta_2\right) \tag{16}$$

Substituting (15) and (16) into (13) and (14), respectively, results in the following disturbance estimation error dynamics

$$\dot{z}_1 = -\frac{\partial \beta_1}{\partial e_2} z_1 \tag{17}$$

$$\dot{z}_2 = -\frac{\partial \beta_2}{\partial e_4} z_2 \tag{18}$$

Thus, natural selections for β_1 and β_2 are

$$\beta_1(e_1, e_2) = \lambda_1 e_2 \tag{19}$$

$$\beta_2(e_3, e_4) = \lambda_2 e_4 \tag{20}$$

where λ_i can be an adjustable positive constant, $i = 1, 2$.

Lemma 3.1. *For the error estimation system (13), if we choose the smooth function (19) and design the adaptive law (15), the closed-loop system is global exponential stable.*

Proof: Substituting (19) into (17) yields $\dot{z}_1 = -\lambda_1 z_1$, since $\lambda_1 > 0$, closed-loop system is global exponential stable, that is, disturbance estimation error z_1 converges to zero exponentially, i.e., $\lim_{t\to\infty} z_1 = 0$, which demonstrates that the manifold $M_1 = \left\{\left(e_1, e_2, \hat{d}_1\right) \middle| \hat{d}_1(t) + \beta_1(e_1, e_2) - d_1(t) = 0\right\}$ of z_1 is invariant and attractive. Hence, it can improve the convergence performance of the estimation error by selecting the gain of the adaptive law properly.

Lemma 3.2. *For the error estimation system (14), if we choose the smooth function (20) and design the adaptive law (16), the closed-loop system is global exponential stable.*

Proof: Since the process is similar to Lemma 3.1, it is omitted here.

4. Control Design and Stability Analysis.

4.1. Design of controller.
On the basis of the aforementioned decomposition technique, we choose an optimal control law for the minimum phase dynamics (9)

$$v_2 = -l_1 e_3 - l_2 e_4 - \hat{d}_2 - \beta_2(e_3, e_4) \tag{21}$$

where $(l_1, l_2) = \boldsymbol{K} = \boldsymbol{R}^{-1}\boldsymbol{B}^T\boldsymbol{P}$ is the optimal gain and $\boldsymbol{P}$ is the positive definite solution of the algebraic Riccati equation: $\boldsymbol{PA} + \boldsymbol{A^TP} - \boldsymbol{PBR^{-1}B^TP} = -\boldsymbol{Q}$. $\boldsymbol{R}$ and $\boldsymbol{Q}$ are positive definite and symmetric matrice appropriately.

Note that the minimum phase dynamics is completely decoupled from the non-minimum phase dynamics. It means that the vertical dynamics will not be affected by the aircraft horizontal and roll dynamics. We utilize the sliding mode method to design a controller for system (10) such that the origin of (10) is an asymptotical stable equilibrium.

Let $\mu_1 = e_2$, $\mu_2 = [e_1, \eta_1, \eta_2]^T$, Equation (10) can be rewritten as

$$\begin{aligned} \dot{\mu}_1 &= v_1 + d_1(t) \\ \dot{\mu}_2 &= p\left(e, \eta, \ddot{Y}_d\right) \end{aligned} \tag{22}$$

where

$$p\left(e, \eta, \ddot{Y}_d\right) = \begin{bmatrix} e_2 \\ \frac{1}{\varepsilon}(\eta_2 + e_2\cos\eta_1 + e_4\sin\eta_1) \\ \frac{1}{\varepsilon}(\eta_2 + e_2\cos\eta_1 + e_4\sin\eta_1)(e_2\sin\eta_1 - e_4\cos\eta_1) + \ddot{y}_{d1}\cos\eta_1 + (\ddot{y}_{d2} + g)\sin\eta_1 \end{bmatrix}.$$

Linearizing the second equation of (22) results in

$$\dot{\mu}_2 = A_2\mu_2 + A_1\mu_1 + o\left(e, \eta, \ddot{Y}_d\right) \tag{23}$$

where

$$A_2 = \left.\frac{\partial p\left(e, \eta, \ddot{Y}_d\right)}{\partial e_2}\right|_o = \begin{bmatrix} 1 & \frac{1}{\varepsilon} & 0 \end{bmatrix}^T, \quad A_1 = \left.\frac{\partial p\left(e, \eta, \ddot{Y}_d\right)}{\partial [e_1 \ \ \eta_1 \ \ \eta_2]}\right|_o = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{1}{\varepsilon} \\ 0 & g & 0 \end{bmatrix},$$

$$o\left(e, \eta, \ddot{Y}_d\right) = p\left(e, \eta, \ddot{Y}_d\right) - A_2\mu_2 - A_1\mu_1.$$

It is obvious that (A_2, A_1) is completely controllable.

Define a sliding mode variable for system (22)

$$s = \mu_1 - M\mu_2 \tag{24}$$

Here $M = [m_1 \ \ m_2 \ \ m_3]^T$ can be chosen such that $A_2 + A_1M$ is Hurwitz.

Thus, the sliding mode adaptive controller for system (22) can be designed as:

$$v_1 = Mp - \hat{d}_1 - \beta_1(e_1, e_2) - hsign(s) \tag{25}$$

where h is a positive constant, and $\hat{d}_1$ is given in (11).

4.2. Stability analysis.
To verify the validity of our control strategy, we provide the stability analysis for the proposed controllers.

Theorem 4.1. *The control law consisting of (15) and (21) can force the minimum phase system (9) exponentially stable if the design constants l_i, $i = 1, 2$ are chosen such that the algebraic Riccati equation holds.*

Proof: Substituting (21) into (9) yields the closed-loop system

$$\begin{aligned} \dot{e}_3 &= e_4 \\ \dot{e}_4 &= -l_1 e_3 - l_2 e_4 + z_2 \end{aligned} \tag{26}$$

From aforementioned argument, we have $\lim_{t\to\infty} z_2 = 0$, then the closed-loop minimum phase system is exponentially stable and hence, for any differentiable output command $Y_d = (y_{1d}, y_{2d})$, $y_2 = x_3 \to y_{2d}$ and $\dot{y}_2 = x_4 \to \dot{y}_{2d}$ as $t \to \infty$.

Theorem 4.2. *The control law consisting of (16) and (25) can force the non-minimum phase system (10) exponentially stable if we choose the sliding mode surface (24) and the design constant vector M such that $A_2 + A_1 M$ is Hurwitz.*

Proof: Consider the Lyapunov function

$$V = \frac{1}{2} s^2 \tag{27}$$

Taking the time derivative of (27), and substituting into (15) and (26) yield

$$\dot{V} = s\dot{s} = s\left(\dot{\mu}_1 - M\dot{\mu}_2\right) = -z_1 s - h_2 |s|$$

Seeing that z_1 converges to zero exponentially, we can obtain $\dot{V} < 0$. There exists time t_s, for $t \geq t_s$, such that $s = 0$. Therefore, for $t \geq t_s$, we have

$$\dot{\mu}_2 = A_2\mu_2 + A_1\mu_1 + o\left(e, \eta, \ddot{Y}_d\right) = (A_2 + A_1 M)\mu_2 + o\left(e, \eta, \ddot{Y}_d\right) \tag{28}$$

Since $o\left(e, \eta, \ddot{Y}_d\right)$ is high-order item and $A_2 + A_1 M$ is Hurwitz, the closed-loop non-minimum phase part is exponentially stable, so it follows that $e_1 \to 0$, $\eta_1 \to 0$ and $\eta_2 \to 0$ as $t \to \infty$, i.e., $y_1 \to y_{1d}$, as $t \to \infty$. Furthermore, noticing $s = 0$ we arrive at $e_2 \to 0$ as $t \to \infty$, i.e., $y_1 \to y_{1d}$, as $t \to \infty$. In light of (5), we can further deduce that $x_5 \to 0$ and $x_6 \to 0$ as $t \to \infty$. Hence, the internal dynamics of original system (2) is stable.

5. **Simulation Results.** In the following, we use a numerical simulation to illustrate the effectiveness of the proposed method with $\varepsilon = 0.5$. Gravity acceleration $g = 9.8$. The estimation and control gains are chosen as: $\lambda_1 = 50$, $\lambda_2 = 20$, $h = 2$, $l_1 = 1.4142$, $l_2 = 2.1974$, $\boldsymbol{Q} = \text{diag}(100, 100)$, $\boldsymbol{R} = 50$. The input disturbances are $\xi_1(t) = \xi_2(t) = 0.5 \sin t$. The initial conditions are taken as $x(0) = [1.4 \;\; 0.01 \;\; -0.5 \;\; 0.01 \;\; 0.05 \;\; 0]^T$, and the reference trajectory is $y_{d1} = \cos t$, $y_{d2} = \sin t$.

The simulation results are shown in Figures 1 to 4. Figure 1 shows that the position tracking errors asymptotically converge to zero within 6s, while Figure 2 illustrates that the attitude and angular velocity also converges fast. This means that the presented controllers exhibit considerable tracking performance in the presence of input disturbances. Figure 3 is the control input curves. Figure 4 presents the results of the disturbance estimation, and it can be seen that the disturbance estimation $\hat{d}_1$ and $\hat{d}_2$, respectively converge to d_1 and d_2 within 0.5s, implying that the adaptive I&I disturbance estimator also exhibits excellent performance to deal with the disturbances. Consequently, the proposed method is effective and feasible.

6. **Conclusions.** A robust control strategy based on adaptive I&I control to achieve output tracking for a non-minimum VTOL aircraft with input-dependent disturbance has been proposed. To attenuate the effects of input disturbances, we construct an adaptive I&I disturbance estimator. The design of disturbance estimator separates from the controller, which makes the resulting modular adaptive controllers easier to tune compared to classical adaptive control method. Then, on the basis of the adaptive I&I disturbance estimator, the system decomposition, the optimal control and the sliding mode control, two low-dimensional controllers have been designed for both the minimum phase and the

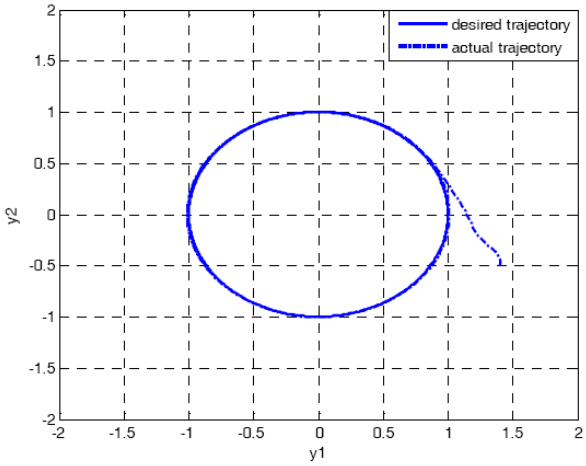

Figure 1. The output tracking curves

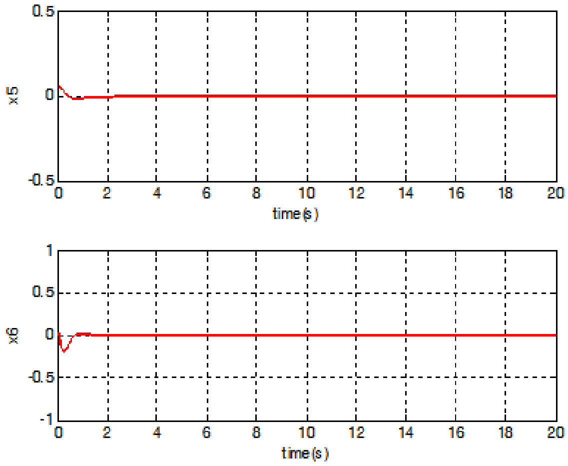

Figure 2. The roll angle and angle velocity

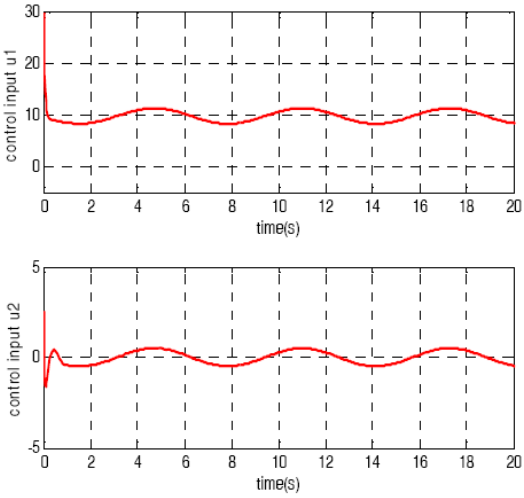

Figure 3. Control input

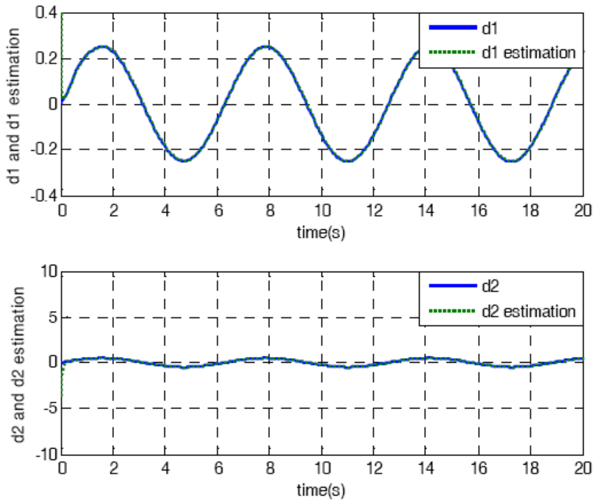

Figure 4. Disturbance estimation

non-minimum phase subsystems. The resulting controllers not only force the VTOL aircraft to asymptotically track the desired trajectories but also keep the internal dynamics stable. Finally, simulation results have verified the validity and robustness of the proposed controllers.

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