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A New State Observer and Flight Control of Highly Maneuverable Aircraft

Ming Xin and S.N. Balakrishnan

Abstract— In this paper, a new nonlinear observer (θ-D observer) is proposed to estimate the feedback states for optimal control of a highly maneuverable aircraft. This observer is derived by constructing the dual of a recently developed nonlinear optimal control technique known as the θ-D technique. The θ-D optimal control approach provides an approximate closed-form solution to the Hamilton-Jacobi-Bellman (HJB) equation. An optimal flight controller using this technique is designed for a highly maneuverable aircraft operating at high angle of attack where the θ-D observer is employed to estimate the states for feedback. The structure of this observer is similar to the State Dependent Riccati Equation Filter (SDREF). However, the new method provides a closed-form observer gain and does not need time-consuming online computations of the algebraic Riccati equation at each instant as the SDREF. The theoretical results about this new observer are given. The simulation shows that the θ-D control and observer exhibit excellent performance for this flight control problem.

I. INTRODUCTION

Observer design for nonlinear systems has been an active field of research over the last few decades. Two primary approaches and their variations have been extensively studied. One well-established method is the exact error linearization [1-3] that is based on a nonlinear state transformation by which the error dynamics of state is linear so that the design of state observer can be performed using linear techniques. However, its integrability condition limits its possible applications and the need to solve a system of partial differential equations complicates the design process. The second approach involves high-gain techniques [4-7]. The system in consideration possesses a structure with a linear and nonlinear part. A linear observer is designed such that the linear part dominates the nonlinearity. Lipschitz condition is assumed to hold for the nonlinear part and the Lipschitz constant is needed to determine the eigenvalues of the error dynamics for stability.

Extended Kalman Filter [8] and its variations are widely used as well in stochastic settings. Since linearization about the current estimate is used to compute observer gain, these methods cannot guarantee the performance for highly nonlinear systems. A relatively new estimation approach called State Dependent Riccati Equation Filter (SDREF) [9] has received much attention during the last decade. SDREF does not include any linearization like the EKF but needs iterative on-line solution to the algebraic Riccati equation at each instant, a process that is computationally intensive. Also stability of the SDREF has not been well established.

In this paper, a new nonlinear observer, called the θ-D observer is proposed as state estimation of nonlinear systems. The observer is derived from duality of a recently developed nonlinear optimal control method called the θ-D technique [10]. This observer takes the same structure as the SDREF. However, the θ-D observer provides a closed-form observer gain. In this work, the θ-D technique is used to design a closed-form optimal flight control law for a highly maneuverable aircraft with nonlinear dynamics and the θ-D observer is utilized to estimate the aircraft states for feedback.

Since the new observer is derived from the θ-D control technique, this nonlinear control method is reviewed in Section II. The development of the θ-D observer and its associated theoretical results are presented in Section III. Applications to the flight control and simulation results are shown in Section IV. Some concluding remarks are given in Section V.

II. REVIEW OF θ-D CONTROL TECHNIQUE

The θ-D nonlinear control technique addresses the class of nonlinear time-invariant systems described by

\[ \dot{x} = f(x) + Bu \]  

with the cost functional:

\[ J = \frac{1}{2} \int_0^\infty [x^T Q x + u^T R u] dt \]

where \( x \in \Omega \subseteq \mathbb{R}^n \), \( f : \Omega \rightarrow \mathbb{R}^n \), \( B \in \mathbb{R}^{n \times m} \), \( u \in \mathbb{R}^m \), \( Q \in \mathbb{R}^{n \times n} \), \( R \in \mathbb{R}^{m \times m} \); \( Q \) is a positive semi-definite matrix and \( R \) is a positive definite matrix; \( B \) is a constant matrix and \( f(0)=0 \); \( \Omega \) is a compact subset in \( \mathbb{R}^n \); Assume that \( f(x) \) is continuously differentiable and zero state observable through \( Q \).

The optimal solution to this infinite-horizon nonlinear regulator problem can be obtained by solving the Hamilton-Jacobi-Bellman (HJB) partial differential equation [11]:

\[ \frac{\partial V}{\partial x} f(x) - \frac{1}{2} \frac{\partial V^T}{\partial x} B R^{-1} B^T \frac{\partial V}{\partial x} + \frac{1}{2} x^T Q x = 0 \]

where \( V(x) \) is the optimal cost, i.e.

\[ V(x) = \min_{u \in \mathbb{R}^m} \frac{1}{2} \int_0^\infty [x^T Q x + u^T R u] dt \]

Optimal control is obtained from the necessary condition as
\[ u = -R^{-1}B^T \frac{\partial V}{\partial x} \]  
\[ \text{(5)} \]

The \( \theta - D \) control technique provides an approximate solution to the above HJB equation such that a suboptimal closed-form feedback controller can be obtained.

The \( \theta - D \) control method can be summarized by the following procedure \[10\].

Write the original nonlinear state equation as:
\[ \dot{x} = f(x) + Bu = \left[ A_0 + \theta \frac{A(x)}{\theta} \right] x + Bu \]  
\[ \text{(6)} \]
where \( A_0 \) is a constant matrix such that \( (A_0, B) \) is a stabilizable pair and \( \{f(x), B\} \) is pointwise controllable.

Add a perturbation series \( \sum_{j=1}^{\infty} D_j \theta^j \) to the cost function \( (2) \),
\[ J = \frac{1}{2} \int_0^T \left[ x^T (Q + \sum_{j=1}^{\infty} D_j \theta^j) x + u^T R u \right] dt \]  
\[ \text{(7)} \]
where the usage of this series will be elaborated afterward.

Assuming a power series expansion \( \frac{\partial V}{\partial x} = \sum_{j=0}^{\infty} T_j(x, \theta) \theta^j x \) and solving the perturbed optimal control problem \( (6) \) and \( (7) \) through the HJB equation yield a suboptimal control
\[ u = -R^{-1}B^T \sum_{j=0}^{\infty} T_j(x, \theta) \theta^j x \]  
\[ \text{(8)} \]
where \( T_j(x, \theta) \) is a symmetric matrix and is solved recursively by the following algorithm.
\[ T_0 A_0 + A_0^T T_0 - T_0 B R^{-1} B^T T_0 + Q = 0 \]  
\[ \text{(9a)} \]
\[ T_i (A_0 - BR^{-1} B^T T_i) + (A_i^T - T_i BR^{-1} B^T T_i) \eta_i = -T_{n-i} A(x) - \frac{A(\eta)}{\theta} T_{n-i} - D_i \]  
\[ \text{(9b)} \]
\[ \vdots \]
\[ T_n (A_0 - BR^{-1} B^T T_n) + (A_n^T - T_n BR^{-1} B^T T_n) \eta_n = -T_{n-1} A(x) - \frac{A(\eta)}{\theta} T_{n-1} - D_n \]  
\[ \text{(9c)} \]
Equation \( (9a) \) is an algebraic Riccati equation. The rest of the equations are Lyapunov equations that are linear in terms of \( T_i \) \( (i=1,2,\ldots,n) \). Since all the coefficients of \( T_i \) are the same constant matrices, i.e. \( A_0 - BR^{-1} B^T T_i \) and \( A_i^T - T_i BR^{-1} B^T \), closed-form solution for \( T_i(x, \theta) \) can be easily obtained by solving Eqs. \( (9a)-(9c) \) successively \[10\].

The \( D_i \) matrix is constructed in the form of:
\[ D_i = k_i e^{-i} \left[ -T_{n-i} A(x) - \frac{A(\eta)}{\theta} T_{n-i} \right] \]  
\[ \text{(10a)} \]
\[ \vdots \]
\[ D_n = k_n e^{-i} \left[ -T_{n-1} A(x) - \frac{A(\eta)}{\theta} T_{n-1} + \sum_{j=1}^{n-i} T_j BR^{-1} B^T T_{n-j} \right] \]  
\[ \text{(10b)} \]
where \( k_i \) and \( l_i > 0 \) are design parameters such that
\[ \frac{\partial V}{\partial x} = \sum_{j=1}^{\infty} D_j \theta^j x \]  
\[ \text{(11)} \]
where \( e_i = 1 - k_i e^{-i} (i = 1, \ldots, n) \).

\( \epsilon_i \) is a small number chosen to overcome the large control problem because the state dependent term \( A(x) \) on the right-hand side of the equations \( (9b)-(9c) \) may cause large magnitude of \( T_i(x, \theta) \) if the initial states are large.

\( \epsilon_i \) is also required in the proof of convergence and stability of the above algorithm \[10\]. The exponential term \( e^{-i} \) lets the perturbation terms in the cost function \( (7) \) diminish as time evolves since we don’t want the perturbation terms to change the original cost function too much. \( k_i \) and \( l_i \) are also used to modulate system transient performance. A systematic method to determine these parameters can be referred to \[10,12\].

Remark 2.1 \( \theta \) is just an intermediate variable. The introduction of \( \theta \) is for the convenience of power series expansion, and it is cancelled when \( T_i(x, \theta) \) multiply \( \theta^i \) in the final control calculations, i.e., equation \( (8) \) \[10\]. The cancellation will be clearly seen in the \( \theta - D \) observer development in the next section.

Theoretic results concerning the convergence of the series \( \sum_{j=0}^{\infty} T_j(x, \theta) \theta^j \), closed-loop stability, and optimality of truncating the series can be found in Ref. \[10\].

III. FORMULATION OF \( \theta - D \) OBSERVER

Considering duality property between the linear optimal regulator and observer, we can formulate the observer counterpart of the \( \theta - D \) controller.

Consider the nonlinear system described by
\[ \dot{x} = f(x) \]  
\[ y(x) = Hx \]  
\[ \text{(12)} \]
\[ \text{(13)} \]
where \( f(x) \) is assumed to be of class \( C^1 \), and \( H \) is a constant matrix. Rewrite \( (12) \) as:
\[ \dot{x} = f(x) = F(x)x = \left[ A_0 + \theta \frac{A(x)}{\theta} \right] x \]  
\[ \text{(14)} \]
The \( \theta - D \) observer is given by
\[ \dot{x} = A_0 + \theta \frac{A(x)}{\theta} \dot{x} + K_j (\dot{x}) [y(x) - H \dot{x}] \]  
\[ \text{(15)} \]
where \( K_j (\dot{x}) = P(\dot{x}) H^T V^{-1} \); \( P(\dot{x}) = \sum_{j=0}^{\infty} \dot{T}(\dot{x}, \theta) \theta^j \)
\[ \dot{x} \text{ is the estimate state and } \dot{T}(\dot{x}, \theta) \text{ is the solution to the following equations:} \]
The solution is the solution to the Riccati equation (17a). 

\[
\theta \neq 0
\]

\[
\hat{T}_n = \frac{1}{\theta} \hat{T}_n
\]

where \( \hat{T}_n \) is the solution to

\[
\hat{T}_n(A'_0 - H^T V^{-1} H \hat{T}_0) + (A_0 - \hat{T}_n H^T V^{-1} H) \hat{T}_n = -\varepsilon \left( \hat{T}_n A + A' \hat{T}_n \right) - \sum_{j=1}^{n-1} \hat{T}_j H^T V^{-1} H \hat{T}_{n-j}
\]

Therefore, proving the convergence of \( \sum_{i=0}^{n} \hat{T}_i(\check{x}, \theta) \theta' \) is equivalent to proving the convergence of \( \sum_{i=0}^{n} \hat{T}_i(\check{x}) \) because \( \theta' \) gets cancelled as seen from (22) and (23). Note that this proof substantiates the Remark 2.1.

The objective now is to find a norm bound for each \( \hat{T}_i \) in order to prove the convergence of the series \( \sum_{i=0}^{n} \hat{T}_i(\check{x}) \).

Given a Lyapunov equation \( \hat{A}' \hat{P} + \hat{P} \hat{A} = -\hat{Q} \) (25) if \( \hat{A} \) is a stable matrix, the norm bound for \( \hat{P} \) exists \[14\]

\[
\|\hat{P}\| \leq \mu_{\text{max}}(\hat{A}) - \mu_{\text{min}}(\hat{A})
\]

where \( \mu_{\text{min}}(\hat{A}) \) is a matrix measure of \( \hat{A} \) induced from \( \|\| \).

In the case of 2-norm, \( \mu_{\text{min}}(\hat{A}) \approx \frac{1}{2} \lambda_{\text{max}}(\hat{A} + \hat{A}') \) (27)

In the following, \( \|\| \) is defined as a 2-norm and denotes \( \mu() = \mu_{\text{min}}(\hat{A}) \).

Since \( (A_0, H) \) is an observable pair, \( (A'_0, H') \) is controllable. So the condition (ii) implies that the Riccati equation (17a) has a positive definite solution \( \hat{T}_0 \) and \( A_0 - \hat{T}_0 H^T V^{-1} H \) is a stable matrix.

Eq. (20) has the form of Eq. (25) and we have from (26):

\[
\|\hat{T}_n\| \leq \frac{1}{\mu \left( A_0 - \hat{T}_0 H^T V^{-1} H \right) - \mu \left( A'_0 - H^T V^{-1} H \hat{T}_0 \right)}
\]

Let

\[
C = \frac{1}{\mu \left( A_0 - \hat{T}_0 H^T V^{-1} H \right) - \mu \left( A'_0 - H^T V^{-1} H \hat{T}_0 \right)}
\]

From condition (iv), we have \( C > 0 \).

Then

\[
\|\hat{T}_n\| \leq C \varepsilon \left[ \hat{T}_n A + A' \hat{T}_n \right] \leq C \varepsilon \left[ \|\hat{T}_n\| \|\hat{A}\| + \|\hat{A}'\| \right]
\]

Since \( A(\check{x}) \) is continuous on a compact set \( \Omega \), it is bounded on \( \Omega \).

Let

\[
C_1 = \max_{\hat{T}} \left( \|A(\check{x})\| + \|A' (\check{x})\| \right)
\]

Then

\[
\|\hat{T}_n\| \leq C \varepsilon C_1 \|\hat{T}_n\|
\]

Condition (iii) also implies that \( C_1 \neq 0 \). If it is zero, the nonlinear system will reduce to the linear system for which the solution is \( \hat{T}_0 \), the solution to the Riccati equation (17a).
For later use, define  
\[ S_0 = \| \hat{T}_0 \| - \| \hat{\bar{T}}_0 \| \]  \hspace{1cm} (33) 
and  
\[ S_1 = \epsilon_i \cdot C \cdot C_1 \cdot \| \hat{T}_0 \| \]  \hspace{1cm} (34) 
Therefore, by choosing sufficiently small \( \epsilon_i \), we can always make \( S_1 / S_0 = \epsilon_i CC_1 < 1 \).

From equation (24), a norm-bounded inequality for \( \hat{T}_z \) becomes  
\[ \| \hat{T}_z \| \leq C \cdot \epsilon_i \cdot \| \hat{T}_z \| + \| \hat{T}_I \| \]  \hspace{1cm} (35) 
Let  
\[ C_{H} \triangleq \| H^T V^{-1} H \| , \]  
and  
\[ C_z \triangleq \sup \{ (1 + \epsilon_i C \hat{T}_0) C_{H} \} . \]  \hspace{1cm} (36) 
Then we get  
\[ \| \hat{T}_z \| \leq \epsilon_i \cdot C_{H} \cdot C_z \cdot \| \hat{\bar{T}}_0 \| \]  \hspace{1cm} (37) 
Let  
\[ S_z = \epsilon_i \cdot C_{H} \cdot C_2 \cdot C_z \cdot \| \hat{\bar{T}}_0 \| \]  \hspace{1cm} (38) 
Then we have  
\[ S_z / S_1 = \epsilon_i \cdot CC_z = O(\epsilon_i) \]  \hspace{1cm} (40) 
Therefore, if \( \epsilon_z \) is picked sufficiently small, we can make  
\[ S_z / S_1 < 1 \]  \hspace{1cm} (41) 
In a similar manner we can derive for \( \hat{T}_a \):  
\[ \| \hat{T}_a \| \leq (\epsilon_i \cdot \cdots \cdot \epsilon_i) \cdot \| \hat{T}_a \| \]  \hspace{1cm} (42) 
Once the bound for each \( \hat{T}_i \) is determined, the convergence of the series \( \sum_{i=0}^\infty \hat{T}_i \) can be proved.

Define a series \( \sum_{i=0}^\infty S_x \) with \( S_0 \) and \( S_1 \) defined in (33) and (34) and  
\[ S_x = (\epsilon_i \cdots \epsilon_i) \cdot CC_2 \cdots C_\infty \cdot \| \hat{\bar{T}}_0 \| \]  \hspace{1cm} (43) 
Then  
\[ S_x / S_{x-1} = \epsilon_i \cdot CC_x = O(\epsilon_x) \]  \hspace{1cm} (44) 
By choosing a sufficiently small \( \epsilon_x \) such that \( \lim_{x \to \infty} \epsilon_x CC_x = 1 \), \[ \sum_{i=0}^\infty S_x \] is a convergent series. Since each \( \| \hat{T}_i \| \leq S_x \), \( \sum_{i=0}^\infty \hat{T}_i \) is also a convergent series. Thus \( \sum_{i=0}^\infty \hat{T}_i (\hat{x}, \theta) \theta^i \) is convergent. □

The following lemma shows the asymptotic stability of the \( \theta - D \) observer.

**Lemma 3.1:** Suppose that \( f_i(x) = A(x) x \) is Lipschitz continuous on a compact set \( \Omega \subset R^n \) with \( x, \hat{x} \in \Omega \) and the conditions in Theorem 3.1 are satisfied, then the error dynamics defined by \( \epsilon = \hat{x} - x \) is asymptotically stable.

**Proof.** Rewrite Eqs. (14) and (15)  
\[ \hat{x} = A_x x + f_i(x) \]  \hspace{1cm} (45) 
\[ \hat{x} = A_y \hat{x} + f_i(\hat{x}) + K_y (\hat{x}) [ y(x) - H \hat{x} ] \]  \hspace{1cm} (46) 
Define  
\[ \epsilon = \hat{x} - x \]  \hspace{1cm} (47) 
Then  
\[ \hat{\epsilon} = \hat{x} - \epsilon = [A_x - K_y (\hat{x}) H] \epsilon + [f_i(\hat{x}) - f_i(x)] \]  \hspace{1cm} (48) 
Using (16) in \( \hat{\epsilon} \) yields  
\[ \hat{\epsilon} = [A_\theta - \hat{\bar{T}}_\theta H^T V^{-1} H] \epsilon - \sum_{i=1}^{\infty} \hat{T}_i H^T V \epsilon \hat{T}_i H + [f_i(\hat{x}) - f_i(x)] \]  \hspace{1cm} (49) 
From the condition (ii) in Theorem 3.1, we can always make \( A_\theta - \hat{\bar{T}}_\theta H^T V^{-1} H \) a Hurwitz matrix. 
Let  
\[ F_0 = A_\theta - \hat{\bar{T}}_\theta H^T V^{-1} H \]  \hspace{1cm} (50) 
Thus for any given positive-definite matrix \( \hat{Q} \in \mathbb{R}^{n \times n} \), there exists a unique positive-definite \( \hat{P} \in \mathbb{R}^{n \times n} \) such that  
\[ F_0^T \hat{P} + \hat{P} F_0 = -2\hat{Q} \]  \hspace{1cm} (51) 
Now consider the following positive definite Lyapunov function  
\[ V(\epsilon) = e^T \hat{P} e \]  \hspace{1cm} (52) 
\[ V(\epsilon) = e^T \hat{P} e + \epsilon \hat{\epsilon} \hat{P} e - \sum_{i=1}^{\infty} \hat{T}_i H^T V \epsilon \hat{T}_i H + [f_i(\hat{x}) - f_i(x)] \]  \hspace{1cm} (53) 
Since \( f_i(\hat{x}) \) is Lipschitz continuous on a compact set \( \Omega \), we have  
\[ \| f_i(\hat{x}) - f_i(x) \| \leq L_f \| \hat{x} - x \| = L_f \| \epsilon \| , \]  where \( L_f \) is the Lipschitz constant. Then  
\[ V(\epsilon) \leq -2\lambda_{\min}(\hat{Q}) \| \epsilon \|^2 + 2L_f \| \epsilon \| + 2 \| \hat{T}_i H^T V \epsilon \hat{T}_i H \| \| \epsilon \| \| \hat{T}_i H \| \]  \hspace{1cm} (54) 
From (42), as long as we choose proper \( \epsilon_i \) for \( \sum_{i=0}^{\infty} \hat{T}_i \) and large enough \( \lambda_{\min}(\hat{Q}) \) such that  
\[ \| \hat{P} \| \leq L_f + \sum_{i=0}^{\infty} \| \hat{T}_i H \| \]  \hspace{1cm} (55) 
then we have \( V(\epsilon) < 0 \). Therefore, \( \epsilon = 0 \) is an asymptotically stable equilibrium point. □

**Remark 3.1** The selection of \( k_i \) and \( l_i \) parameters in \( D_i \) and \( \hat{D}_i \) can be done systematically by utilizing the least-square curve fitting of the maximum singular value of the \( \theta - D \) solution with the state dependent Riccati equation solution [10,12].

**IV. APPLICATION TO FLIGHT CONTROL OF AIRCRAFT**

In this section, the \( \theta - D \) observer and control are applied to the flight control of a high performance aircraft operating at high angles of attack. The mathematical model used in this study is similar to the X-31 research aircraft [15] and only the longitudinal mode is considered. The longitudinal model is highly nonlinear at high angle of attack and the conventional linear time invariant framework is not

5383
The commanded control technique. This observer is estimated by using the algorithm (9) and (16) are sufficient for good performance. The $k_1$ and $l_1$ parameters for both control and observer are chosen to be $k_1 = k_2 = 1$, and $l_1 = l_2 = 0.01$.

Figures 1 and 2 show the responses of the angle of attack, pitch rate, and flight path angle respectively. As can be seen, the estimated states converge to the actual states very quickly. The optimal control regulates the states to zero with good transient responses. Figure 3 gives the canard deflection and control command (optimal control), which does not demand large control.

The second scenario is to track a command flight path angle $\gamma_c$. The commanded $\gamma_c$ starts from 0 and gradually increases to 45°, holds until 15 seconds, and then returns to 0 at 20 seconds as shown in Fig. 4. The initial condition is at zero and the initial estimated state starts slightly off the actual, i.e. $x(0) = \begin{bmatrix} 0 & 20 & 0 & 20 & 0 \end{bmatrix}^T$.

In order to ensure a good tracking performance, an integral state of the flight path angle is augmented into the original state space, i.e.

$$\gamma_i = \gamma$$ (59)

The state space for this tracking problem becomes

$$x = \begin{bmatrix} \Delta V & \Delta \alpha & q & \gamma & \Delta \delta \gamma_i \end{bmatrix}^T$$ (60)

and the associated $A_z$ and $A_{nl}$ matrices are changed accordingly. The optimal control is applied as a servomechanism formulation for this tracking problem [13],

$$u(x) = -R^{-1}B^T \sum_{i=0}^{\infty} T_i(\hat{x}, \theta) \phi^T [\hat{x} - \hat{x}]$$ (61)

where $\hat{x} = \begin{bmatrix} 0 & 0 & 0 & \gamma_c & 0 & 0 \end{bmatrix}^T$ is the command state vector. The $k_i$ and $l_i$ parameters are the same as those in the first scenario. Weights used for control and estimation are chosen to be $Q = \text{diag}(1, 1, 1, 100, 1, 200)$, $R = 10$, $W = I_5$, $V = \text{diag}(0.01, 0.01)$.

Figure 4 and 5 show the flight path angle tracking and angle of attack response respectively. As can be seen, the $\theta-D$ control and observer exhibit excellent tracking performance. For comparison, the extended Kalman filter (EKF) is used as a nonlinear observer for the $\theta-D$ optimal control. The results in the first scenario are not much different from using the $\theta-D$ observer. However, in the second flight path angle tracking scenario, the EKF exhibits much worse performance as seen in Figs 6 and 7.

V. CONCLUSIONS

In this paper, a new nonlinear observer was developed from the dual of the $\theta-D$ control technique. This observer does not involve a linearization process required by EKF and address the nonlinearity directly. The major advantage of this observer is that the observer gain can be obtained as a closed-form expression and consequently does not need complex on-line computations compared to the SDREF technique. The $\theta-D$ observer combined with the $\theta-D$ optimal control is applied to the flight control of a highly maneuverable aircraft with high nonlinearity and unstable dynamics. The effectiveness of this technique has been demonstrated by regulating the high angle of attack and tracking flight path angle command.

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