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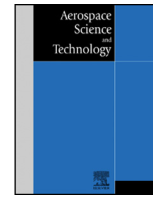

Reset observer design for time-varying dynamics: Application to WIG crafts

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A R T I C L E I N F O

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In this article, a novel reset state estimator for time-varying dynamics is proposed. A first order reset law is used in the structure of observer to improve the performance of the state estimation response which decreases the settling time and overshoot of estimation. The sufficient conditions for stability of this observer based on systems with impulsive effect is addressed which is the main contribution of this study. This observer is applied to a WIG (Wing-In-Ground) craft in the presence of wave and gust which can be modeled by a linear time-varying dynamics. Finally, the five states for longitudinal dynamics of the WIG craft based on a full-order reset observer with time-varying parameters are estimated. The sufficient stability conditions of WIG state observer are stated and simulation results show the superior performance of the reset law.

1. Introduction

Many aerodynamic processes such as Wing-In-Ground (WIG) crafts in extremely ground effect region have complex dynamics, especially in the presence of disturbances. External disturbances such as wave and gust can change the parameters of vehicle to time-varying ones. To have high performance control for these vehicles, an appropriate time-varying observer should be designed. The structure of this observer should have elements with special features which can overcome the limitations of common observers. These features should increase the functionality and flexibility of the observer for complex plants and the estimator should estimate the time-varying dynamic states of the system with high accuracy and acceptable performance. Using reset elements is one of the most outstanding techniques which can be used as an appropriate approach for complex and time-varying systems to estimate the states of plants. One important issue for reset observer is the stability and convergence region of observer with reset element which should be investigated, precisely.

Time-varying observer design has been studied in many articles since 1980. For linear continuous time-varying systems Lovass-Nagy et al. [1] developed a method to deal with the problem of finding observer coefficients. The method is based on matrix generalized inverse which is introduced in [2]. Several studies can be found in time-varying observers for discrete-time stochastic systems such as [3–5] which uses Kalman filter for estimation.

In [6], the state estimation problem is considered for linear time-varying continuous systems with non-lexicographic-fixed observability basis. A two-stage design strategy is presented for constructing observers for this class of systems.

A numerical algorithm in [7] is developed for design of observers for linear time varying descriptor systems for which the observer estimates are also physically correct in that they satisfy the same constraints as the solutions of the descriptor system. Another algorithm for recursive joint estimation of state and parameters in continuous-time state space systems is proposed in [8]. It improves the consistency of an adaptive observer for a system and this modification is inspired by the classic recursive least squares (RLS) algorithm with exponential forgetting factor. Trumpf [9] gives characterizations and necessary and sufficient existence conditions for tracking and asymptotic observers for linear functions of the state of a linear finite-dimensional time-varying state space system. A functional observer for linear time-varying systems based on Lovass-Nagy method in [10] was developed. Interval state observer for nonlinear time varying systems has been developed in [11] and [12].

One of the methods to enhance the response of systems is impulsive dynamical system framework or reset control systems. Resetting law was introduced by Clegg [13] for the first time who proposed an integrator which was reset to zero when its input is zero. This idea was improved in many articles [14–18]. This process

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Nomenclature

System and observer variables

$x(t), u(t), y(t)$	System states, input and output
$A(t), B(t), C(t)$	System matrices
$\hat{x}(t), \hat{y}(t)$	Estimated system state and output
$\tilde{x}(t), \tilde{y}(t)$	Error system state and output
K_P, K_I	Proportional and integral gains
ζ	Reset term
A_ζ, B_ζ	Reset scalars
A_R	Reset Gain
F, J	Flow-set and Jump-set
η	Augmented error
A_η, B_η	Augmented error matrices
τ_i	Reset instances
χ	Characteristic exponent
$\Re$	Number of impulses
λ_i, Λ_i	The least and the largest eigenvalues
$\bar{\alpha}, \bar{\gamma}$	Upper bound of eigenvalues
$\underline{\delta}$	Lower bound of eigenvalues

WIG variables and coefficients

u, w, q, θ, h	WIG state variables
$\delta_E, \Delta\tau$	WIG input variables
$X_u, X_w, X_q, X_{\dot{w}}, X_h$ $Z_u, Z_w, Z_q, Z_{\dot{w}}, Z_h$ $M_u, M_w, M_q, M_{\dot{w}}, M_h$	Aerodynamic Stability derivatives
$X_{\delta_E}, X_{\Delta\tau}, Z_{\delta_E}, Z_{\Delta\tau}, M_{\delta_E}, M_{\Delta\tau}$	Input influence coefficients
α	Angle of attack
$C_L, C_{L_0}, C_L^w, C_L^g$	Lift coefficients
$C_m, C_{m_0}, C_m^w, C_m^g$	Pitching moment coefficients
C_D	Drag coefficients
F_L, ψ_L	Amplitude and phase of lift changes
F_m, ψ_m	Amplitude and phase of moment changes
c	Wing chord of vehicle
λ	Wing aspect ratio
m	Mass of WIG
g	Acceleration due to gravity
I_y	Inertia moment about y-axis
ρ	Air density

Wave and gust parameters

a_w	Amplitude of wave
L_w	Length of wave
k	Wave number
κ	Wave number component
β	Course angle of wave
c_0	Wave speed
ω	Wave frequency
ω_e	Encounter frequency
V_g	Maximum velocity of gust

is known as switching, hybrid, reset or impulsive systems which changes the functionality of the closed loop system to a richer behavior compared with normal systems. Resetting element is added to the system and causes jumps at defined conditions on system states. Therefore, the interaction of both continuous and discrete dynamics in reset system results in a rich dynamical behavior and phenomena not encountered in purely continuous-time systems.

In contrast to many well-established observers, which normally estimate the system state in an asymptotic fashion, an observer which estimates the exact system state in predetermined finite time using state updates at time instants is proposed in [19]. Reset adaptive observer which was introduced in [20] and [21] is an adaptive observer consisting of an integrator and a reset law that resets the output of the integrator depending on a predefined condition. This approach has application for LTI framework and some nonlinear classes.

In recent years, different approaches have been introduced on reset controllers and observers for time-varying delay systems [33, 34], improvement of high order reset elements [35] and discrete MIMO reset controllers [36].

In this study, for the first time the reset observer framework for linear time-varying systems is introduced in section 2. The states of the observer have been augmented to the reset term of the reset element. These states jump at specified condition to change the transient response of the system. Moreover, the order of complexity for observer with reset augmented error and without reset feature have been considered in this section. Then in section 3, the sufficient conditions for time-varying reset observer stability are developed. These conditions are based on the analogue of Wazewski's Inequality and characteristic exponent definition. As a case study, the time-varying longitudinal dynamics for a 20-passenger WIG craft in the presence of wave and gust is investigated in section 4. Finally, in last section a reset observer for a WIG craft is designed and simulated to show the performance and effectiveness of the reset observer compared to non-resetting one. Moreover, complementary theorems for stability conditions have been considered in appendices.

2. Reset observer framework

In order to design a reset observer, the linear time-varying system with the following dynamics is considered:

$$\begin{cases} \dot{x}(t) = A(t)x(t) + B(t)u(t) \\ y(t) = C(t)x(t) \end{cases} \tag{1}$$

where $x(t) \in R^{n\times 1}$ is the system state, $u(t) \in R^{m\times 1}$ is the system input, $y(t) \in R$ is the system output, and $A(t) \in R^{n\times n}$, $B(t) \in R^{n\times m}$ and $C(t) \in R^{1\times n}$ are time-varying matrices with appropriate dimensions.

For the problem of state estimation of the above linear time-varying system, an observer with following dynamics is proposed:

$$\begin{cases} \dot{\hat{x}}(t) = A(t)\hat{x}(t) + B(t)u(t) + K_P\tilde{y}(t) + K_I\zeta(t) \\ \hat{y}(t) = C(t)\hat{x}(t) \end{cases} \tag{2}$$

where $\hat{x}(t)$ and $\hat{y}(t)$ are the estimated states and output, K_P and K_I represent the proportional and integral gain respectively and $\tilde{y}(t) = y(t) - \hat{y}(t)$ is the output estimator error. The structure of reset observer is shown in Fig. 1. In (2), $\zeta(t) \in R$ is the reset integral term which can be computed as:

$$\begin{cases} \dot{\zeta}(t) = A_\zeta\zeta(t) + B_\zeta\tilde{y}(t) & \tilde{y}\cdot\zeta \geq 0 \\ \zeta(t^+) = A_r\zeta(t) & \tilde{y}\cdot\zeta \leq 0 \end{cases} \tag{3}$$

where $A_\zeta \in R$ and $B_\zeta \in R$ are two tuning scalars which regulate the transient response of ζ, and A_r is the reset gain or generally reset matrix. If A_r is chosen equal to zero, the reset integral term ζ is reset to zero. Furthermore, the value of the variable ζ after switching is denoted by $\zeta(t^+)$.

By defining $\tilde{x}(t) = x(t) - \hat{x}(t)$ as the state error, the error dynamics will be achieved by subtracting (1) and (2):