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State and actuator fault estimation observer design integrated in a riderless bicycle stabilization system

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A B S T R A C T

This paper deals with an observer design for Linear Parameter Varying (LPV) systems with high-order time-varying parameter dependency. The proposed design, considered as the main contribution of this paper, corresponds to an observer for the estimation of the actuator fault and the system state, considering measurement noise at the system outputs. The observer gains are computed by considering the extension of linear systems theory to polynomial LPV systems, in such a way that the observer reaches the characteristics of LPV systems. As a result, the actuator fault estimation is ready to be used in a Fault Tolerant Control scheme, where the estimated state with reduced noise should be used to generate the control law. The effectiveness of the proposed methodology has been tested using a riderless bicycle model with dependency on the translational velocity v, where the control objective corresponds to the system stabilization towards the upright position despite the variation of v along the closed-loop system trajectories.

1. Introduction

The Linear-Parameter-Varying (LPV) modeling has represented, over the last few decades, a simple way to approach nonlinear dynamics. This kind of systems belong to the general class of Linear-Time-Varying (LTV) systems [1–3], allowing the approximation of complex systems based on a set of parameters whose value may change along the system trajectories [4]. A LPV system is considered as a parameter-dependent system, in which the control design is defined in terms of causal functions of the time-varying parameter — current control values cannot depend on the future values of the time-varying parameter — in contrast with LTV systems design. The distinction from Linear Time Invariant (LTI) systems is, with the previously commented in mind, clear: the LPV systems are nonstationary [5]. In addressing the LPV representation, several formulations exist: polytopic, Linear Fractional Transformation (LFT) and LPV affine. The polytopic LPV systems have been broadly studied because they provide a suitable representation computed as the combination of linear models — that approach the system behavior at a finite number of operating points — visualized as the vertices of a polytope [6,7]. The LFT representation of LPV systems involves the separation between the varying and the non-varying part of the model [8]. Finally, the affine formulation considers an infinite number of equilibrium points. Within the last case, there is an additional representation which involves dependency on the time-varying parameter on multiple degree: the polynomial LPV systems [9,10]. Such a particular formulation of LPV systems presents a difficult consideration: the stability analysis leads to problems related to Linear

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Matrix Inequalities with dependency on the time-varying parameter, named parameterized Linear Matrix Inequalities (PLMI). In other words, the main difficulty with polynomial LPV systems corresponds to the solution of a PLMI and, consequently, a less studied case. On the other hand, the continued growth of the control systems requires maintain an acceptable level of reliability, in which case the Fault Tolerant Control (FTC) [11] becomes relevant. In this direction, an important issue concerns to the estimation of the fault affecting the system [12–14]. The reason comes intuitively: if the fault magnitude is known, then it is possible to take corrective actions to ensure the control objectives. Such corrective actions may involve the on-line modification of the control gains by considering the fault estimation or the addition of virtual actuators and/or sensors [15]. This can be viewed within a special FTC case: Active Fault Tolerant Control. As a result, the importance of fault estimation lies on the possibility to provide information about the fault to be used in the FTC scheme. Further, the previous information can be also taken as fault indicator, isolation and identification, issue related to the Fault Diagnosis and Isolation (FDI). In terms of control system design, moreover, it is highly desirable the computation of a control law that contributes to a smooth and unforced operation of the actuator of the system, which could hardly be accomplished in the presence of noise at the system outputs. Consequently, the contribution of this paper refers the design of an observer in charge of the estimation of actuator fault and system state, reducing the effect of the noise presented at the system outputs. The previous is achieved by maintaining the stability characteristics of LPV systems. The LPV systems stability, in contrast with the LTI systems stability, is related to the fact that the Lyapunov analysis leads to an expression in which the maximum rate for the time-varying parameter — involved in the system dynamics — is taken into account. Thus, the proposed observer design maintains its stability considering the maximum rate of the time-varying parameter, as a result of the stability conditions for LPV systems. In the model of the considered application, the rate of the time-varying parameter corresponds to the translational acceleration of the bicycle. The proposed observer finds potential applications in FTC schemes due to the fault estimation. The estimated state, on the other hand, could be used to generate a control signal with less noise corruption. In the LPV fault reconstruction literature, [16] designs an observer using the sliding mode methodology for fault estimation with application to a Boeing 747-100 LPV model, through an affine LPV representation. In [17], the fault estimation and its compensation into the closed-loop system are addressed. An affine LPV model of a two-link manipulator is considered, in which the control objectives are maintained through the proposed methodology. Ref. [18] deals with a state observer for affine LPV systems, with a computed solution as a linear combination between the time-varying parameters and their boundaries. Furthermore, for a winding machine system, a polytopic LPV sensor fault detection filter has been developed in [19]. Although the works in these references are applied to LPV systems, the actuator fault estimation remains insufficiently explored in the polynomial LPV systems framework. The previous matter is viewed as the main motivation for the results presented throughout this paper. Consequently, the design of the observer is based on the extension of the LTI robust methodologies to polynomial LPV systems, considering the stability characteristics for this kind of systems. The proposed observer provides the system state and actuator fault estimation, using a polynomial LPV model of a riderless bicycle, affected by an actuator fault and measurement noise. The proposed observer is used to build the control law, by means of the estimated state with less noise than the one presented at the system output. The fault estimation, meanwhile, can be used within FDI or FTC approaches. The paper structure is as follows: Section 2 presents the definition of polynomial LPV systems, as well as their controllability and observability conditions. Section 3 addresses the riderless bicycle model and its dynamical analysis. Section 4 provides the preliminaries on the stabilization of the riderless bicycle polynomial LPV model. Section 5 presents the design of the state and actuator fault estimation observer, besides the controller design. It addresses the observer and control gain computation at the end. Section 6 shows the simulation results considering different types of actuator faults. Finally, a brief discussion is presented in Section 7 and conclusions in Section 8.

2. Polynomial LPV systems

The present section addresses the definition of polynomial LPV systems along with their structural properties. Consider the following dynamical system:

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

where $x \in \mathbb{R}^n$, $u \in \mathbb{R}^p$ and $y \in \mathbb{R}^s$ correspond to the state, input and output (vector) variables, respectively. $A(\zeta(t))$, $B(\zeta(t))$ and $C(\zeta(t))$ represent parameter-dependent matrices of compatible dimensions. $\zeta(t) \in \mathbb{R}^m$ is the time-varying parameter vector. Normally, $\zeta(t)$ is considered measurable and bounded, with bounded time ratio $\zeta(t)$, i.e. $\exists \nu, \nu > 0$ such that $\|\zeta(t)\| \le \nu$ and $\|\dot{\zeta}(t)\| \le \mu$ with $\mu > 0$. If $A(\zeta(t))$, $B(\zeta(t))$ and/or $C(\zeta(t))$ adopt the form

$$\chi(\zeta) = \chi_0 + \sum_{i=1}^{k} \sum_{j=1}^{m} \chi_{\{[(i-1)m]+j\}} \zeta(t)_j^i \tag{2}$$

for some $k \ge 1$, where χ_l, $l = 0, \ldots, km$, are matrices of compatible dimensions (depending on the referred matrix $A(\zeta(t))$, $B(\zeta(t))$ or $C(\zeta(t))$), then the state model (1) corresponds to a polynomial LPV system. As an example (from now on, the argument of ζ will be dropped for the sake of simplicity), consider $\zeta \in \mathbb{R}^2$, i.e. two time-varying parameters ζ_1 and ζ_2 (i.e. $m = 2$). With $k = 2$, Eq. (2) corresponds to

$$\chi(\zeta) = \chi_0 + \chi_1\zeta_1 + \chi_2\zeta_2 + \chi_3\zeta_1^2 + \chi_4\zeta_2^2 \tag{3}$$

As a result, the system dependency in the time-varying parameter vector will appear in polynomial form. In order to show the structural properties for this kind of systems and, according to [20], the controllability condition for polynomial LPV systems can be seen as the extension of this criterion applied to LTI systems. The polynomial LPV system (1), considering the representation (2), is controllable if

$$rank[B(\zeta)\ A(\zeta)B(\zeta) \ldots A(\zeta)^{n-1}B(\zeta)] = n \quad \forall\ \|\zeta\| \le \nu \tag{4}$$

In analogous way, a polynomial LPV system will be observable if

$$rank \begin{bmatrix} C(\zeta) \\ C(\zeta)A(\zeta) \\ \vdots \\ C(\zeta)A(\zeta)^{n-1} \end{bmatrix} = n \quad \forall \|\zeta\| \le \nu \tag{5}$$

3. The riderless bicycle model and its dynamical analysis

The riderless bicycle can be formulated in terms of a general frame which includes a rigid body, a front frame composed by the handle, and the tires. The general representation for this system is given as [21]

$$Q\ddot{q} + vW\dot{q} + (gE_0 + v^2E_1)q = f \tag{6}$$