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Soft Switching System Based on Weighted Probabilities for Stochastic Hybrid Multiple Model-based Control Systems

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Abstract- **Stochastic hybrid model-based control refers to controlling uncertain systems, which are modeled as a multiple-model set with a varying variable structure and the use of interacting multiple model (IMM) estimator and generalized predictive control (GPC) algorithm as described in [1]. For a hard switching system, the plant model is determined by the selection of the "most reliable" model in the model set. However as indicated in [2], the hard switching system can be destabilized with some switching sequences even if every model in the model set is globally stabilized. Now we consider the use of a soft switching system where the plant model is formed by the weighted probabilities from several models in the model set. It provides a smoother and smaller offset error in a tracking process. This paper presents some stabilizability conditions for the soft switching signals of continuous and discrete stochastic hybrid model-based control systems.**

***Index Terms*— Stochastic Hybrid Multiple Model-based Control, Lyapunov Function, Hard Switching System, Soft Switching System.**

1. INTRODUCTION

A switching linear system is a hybrid dynamical system that consists of several linear subsystems and a switching rule that decides which of switching plans is active at each moment. In the last two decades, there has been increasing interest in stability analysis and control design for switching systems [2], [3], [4], [5], [6], [7], [8], [9], [10] and [16]. The motivation for studying switching systems is from the fact that many practical systems are inherently multimodal. Many researchers have studied the use of multiple models in adaptive control of both linear and nonlinear systems in which controllers are switched depending on which model provides the least identification errors. Stability results for such continuous time, switching control systems have been shown for the linear [11] and certain nonlinear cases [12]. The linear multiple model switching is similar to the control of Markovian jump linear systems or the systems that have models whose parameters change according to a Markov chain.

A simplest continuous time hybrid system is described by the following different linear state update equations:

$$\dot{x}(t) = A_i x(t) + B_i u(t) \quad (1)$$

$$z(t) = C_i x(t) \quad (2)$$

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A discrete-time hybrid system is as follows:

$$x(k+1) = A_i x(k) + B_i u(k) \quad (3)$$

$$z(k) = C_i x(k) \quad (4)$$

in which $\left[A_i, B_i, C_i\right]$ are the time i^{th} varying state space model matrices, $i = \{1, 2, ..., N\}$, $x \in \mathbb{R}^n$ is the state vector, $u \in \mathbb{R}^m$ is the control input, and $z \in \mathbb{R}^p$ is the measured output.

When the model uncertainty is present, the exact plant model $\left[A, B, C\right]$ is unknown. The model uncertainty is described by a model set Ω : $\left[A, B, C\right] \in \Omega$ $= Co\left\{\left[A_1, B_1, C_1\right], ..., \left[A_N, B_N, C_N\right]\right\}$, a convex hull of $\left[A, B, C\right] = \sum_{i=1}^{N} \mu_i \left[A_i, B_i, C_i\right]$. The weighting factors μ_i denotes probability satisfying: $\sum_{i=1}^{N} \mu_i = 1$ and $\mu_i \geq 0$.

The exact plant model can be estimated by using an interacting multiple model (IMM) [13]. It runs a bank of IMM estimators in parallel, each based on a particular model, to obtain the model-conditional state estimates $\hat{x}_i(k)$ and the probability $\mu_i(k)$ of each model matching to the exact plant. The hybrid system modeling design is described in [1].

The hard switching system in [1] works as the follows: The plant model is determined by the selection of the "most reliable" model in the model set. Then, we use only one GPC controller to stabilize the closed-loop feedback as shown in Fig. 1(a). However, as indicated in [2], even if each model in the model set is globally stabilized, there can exist a switching sequence that destabilizes the closed-loop dynamics.

Now we consider the use of a soft switching system where a plant model is formed by the weighted probabilities of several models in the model set. Therefore, a bank of GPC controllers is installed where the output of each controller is weighted by its probability vector as shown in Fig. 1(b). As referred to [1], the major advantage of the soft switching system is that it provides a smoother and smaller offset error in a tracking process due to the interaction of model probabilities that are always mixed into the "true" model.

Since the use of linear state stabilizing feedback for the plant model is:

$$u_i = -K_i x_i \quad (5)$$

We have the overall weighted control input $u(t) \approx \sum_{i=1}^{N} \mu_i \hat{u}_i$.

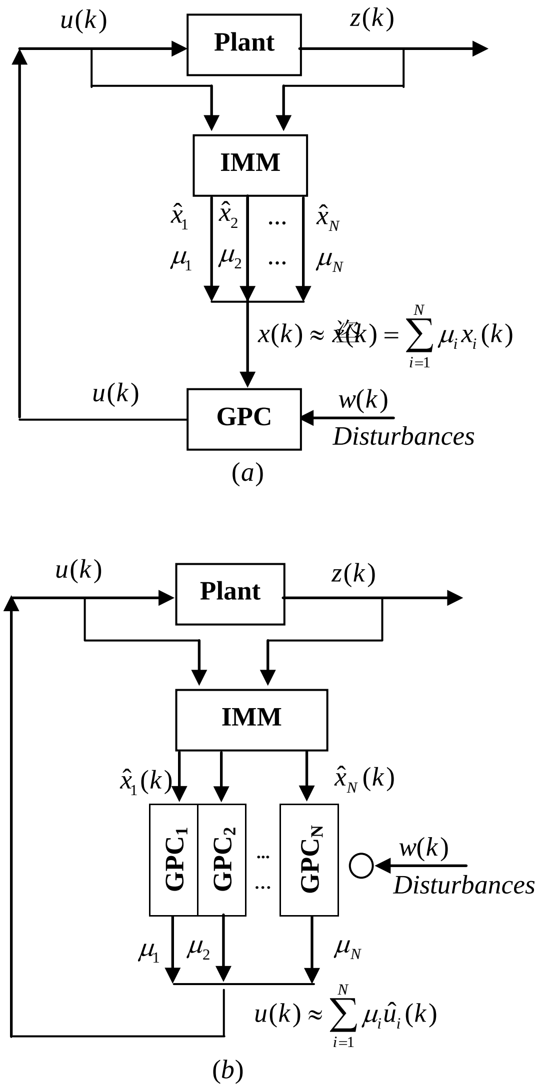

Fig. 1. Diagram of hard and soft switching system

In a hard switching system, the IMM estimator provides the overall state estimate $\hat{x}(k)$ and indicates one "*most reliable*" model $\left[A_i, B_i, C_i\right]$ in the model set. Thus, a stabilizing GPC controller is built up corresponding to this "*most reliable*" model. The hard switching system seems unrealistic since the exact plant model is varying in a convex hull Ω : $\left[A, B, C\right] \in \Omega = \sum_{i=1}^{N} \mu_i \left[A_i, B_i, C_i\right]$.

In a soft switching system, a bank of GPC controllers is used for each model in the model set and the overall control input is weighted by the possibilities of each model: $u(k) = \sum_{i=1}^{N} \mu_i \hat{u}_i(k)$ based on the updated model probabilities μ_i detected by the IMM estimator.

2. Stabilizability of Soft Switching Signals for Continuous-Time

Equations (1), (2) and (5) can be combined to obtain the closed loop state transition matrix for the plant model:

$$A - BK = \sum_{i=1}^{N} \mu_i A_i - \sum_{i=1}^{N} \mu_i B_i K_i = \sum_{i=1}^{N} \mu_i \left(A_i - B_i K_i\right) = \sum_{i=1}^{N} \mu_i A_{CLi}$$

Therefore, we have the closed loop equations:

$$\dot{x}(t) = \sum_{i=1}^{N} \mu_i A_{CLi} x(t) \tag{6}$$

$$z(t) = Cx(t) \tag{7}$$

Now we consider some necessary and sufficient conditions for stabilizing these soft switching signals:

Theorem 2.1*: The soft switching system for the stable closed loop state matrices A_{CLi} in (6) can guarantee the global asymptotical stability for any switching sequence with any plant model if there exists a common positive symmetric definite matrix P and positive symmetric definite matrices Q_i such that $A_{CLi}P + PA_{CLi}^{'} = -Q_i$, $\forall i \in \{1, 2, ..., N\}$.*

Proof: Since all closed loop state matrices A_{CLi} are stable in (6): $\dot{x}(t) = \sum_{i=1}^{N} \mu_i A_{CLi}$. For a positive Lyapunov function $V_i(x) = x^{'}Px$, we have always a negative time derivative $\dot{V}_i(x) < 0$, and the system is stable for any switching sequence with any plant model:

$$\begin{aligned} \dot{V}(x) &= \left(\sum_{i=1}^{N} \mu_i A_{CLi} x\right)^{'} Px + x^{'}P\left(\sum_{i=1}^{N} \mu_i A_{CLi} x\right) \\ &= \sum_{i=1}^{N} \mu_i x^{'}(A_{CLi}P + PA_{CLi}^{'})x = \sum_{i=1}^{N} \mu_i x^{'}(-Q_i)x < 0 \end{aligned} \tag{8}$$

The existence of a direct common Lyapunov matrix $A_{CLi}P + PA_{CLi}^{'} = -Q_i$ among stable matrices A_{CLi} and positive symmetric definite matrices Q_i can be searched with quadratic stability of polytopic systems or directly solved with Linear Matrix Inequalities (LMIs) as referred in [16]. ■

Example 2.1. Consider four stable closed loop state matrices $A_{CL1} = \begin{bmatrix} -0.2 & -0.5 \\ 0.3 & 0.1 \end{bmatrix}$, $A_{CL2} = \begin{bmatrix} -1 & -1 \\ 1 & -1 \end{bmatrix}$, $A_{CL3} = \begin{bmatrix} -2 & 1 \\ 1 & -2 \end{bmatrix}$, and $A_{CL4} = \begin{bmatrix} -2 & -1 \\ 1 & -2 \end{bmatrix}$. By searching Q_i with quadratic stability of polytopic systems, we find out a common Lyapunov matrix for all four matrices: $P_1 = \begin{bmatrix} 0.8928 & 0.4107 \\ 0.4107 & 1.5454 \end{bmatrix}$. By solving directly with LMIs, we can find out another common Lyapunov matrix: $P_2 = \begin{bmatrix} 0.71311 & 0.2920 \\ 0.2920 & 1.0851 \end{bmatrix}$. Hence, we can conclude that the soft switching system for the above four stable closed-loop state matrices is stable for any switching sequence with any plant model.

The conditions for the existence of a common Lyapunov function are not easy to determine at present time. And generally, it is difficult to find a direct common Lyapunov matrix P among stable closed loop state matrices A_{CLi} . In this example, if we only change A_{CL4} into a new one $A_{CL4}^{New}=\begin{bmatrix}-0.25 & 0.5\\ -1 & 0.1\end{bmatrix}$, there is no solution for a common Lyapunov matrix among the above four stable matrices.

The existence of a common Lyapunov matrix can be also derived using the method in [14] and involves the communication relations among the A_{CLi} matrices. Because of the communication, it is easy to derive that if $A_{CLi}A_{CLj}=A_{CLj}A_{CLi}$, then $e^{A_{CLi}t_i A_{CLj}t_j}=e^{A_{CLj}t_j A_{CLi}t_i}$. By direct calculation, it is straight forwards to verify that $\dot{V}(x)<0$ and the switching system is also stable for any switching sequence with any plant model if and only if all the closed-loop state matrices A_{CLi} are Hurwitz and commute pairwise (i.e. $A_{CLi}A_{CLj}=A_{CLj}A_{CLi}$, $\forall i, j$).

The existence of a common Lyapunov matrix, although sufficient, is not necessary for the stability of the switching systems. Now we investigate some other necessary conditions for stabilizability of soft switching systems with an assumption that the derivatives of the Lyapunov functions is upper bounded. Thus, we can always find out positive constant scalars η_i for each model such that:

$$\dot{V}(x)=\sum_{i=1}^{N}\mu_i\dot{V}_i(x)=\left(\sum_{i=1}^{N}\mu_i A_{CLi}x\right)^{'}P_i x+x^{'}P_i\left(\sum_{i=1}^{N}\mu_i A_{CLi}x\right) \le -\eta_i(x^{'}x),\ \forall\mu_i. \qquad (9)$$

The following notation is used, $tr(P)$, $\lambda_{\min}(P)$, $\lambda_{\max}(P)$, denote the trace, the minimum eigenvalue, the maximum eigenvalue of matrix P respectively. Denote $\eta_{\min}=\min_i(\eta_i)$. A new upper bound for the sum of eigenvalues of P_i is found and the switching systems are asymptotically stable.

Theorem 2.2: *Consider the continuous time, stable closed-loop state system described in (6) and (7) and the derivatives of the Lyapunov functions are assumed to be upper bounded as in (9). Suppose that $P_i>0$ is the Lyapunov matrices for each stable closed-loop matrix A_{CLi} . Then, the sum of the eigenvalues of all P_i has an upper bound:* $tr(P_i)\le -\dfrac{tr(\eta_i)}{2\lambda_{\min}(S_{CLi})}$ *where* $S_{CLi}=\dfrac{A_{CLi}+A_{CLi}^{'}}{2}$ *and* $\lambda_{\min}(S_{CLi})<0$.

Proof. Since the derivatives of the Lyapunov functions are assumed to be upper bounded from equation (9), we can write:

$$\sum_{i=1}^{N}\mu_i\left(A_{CLi}P_i+P_iA_{CLi}^{'}\right)\le -\eta_i \qquad (10)$$

Or

$$\sum_{i=1}^{N}\mu_i\left(tr(A_{CLi}P_i)+tr(P_iA_{CLi}^{'})\right)\le -tr(\eta_i) \qquad (11)$$

Using the matrix trace property $tr(AP)=tr(PA)$, we obtain:

$$tr(A_{CLi}P_i)+tr(P_iA_{CLi}^{'})=2tr(P_iS_{CLi})$$

where $S_{CLi}=\dfrac{A_{CLi}+A_{CLi}^{'}}{2}$ (12)

Considering the following inequality in [15]

$$\lambda_{\min}(S)tr(P)\le tr(PS)\le \lambda_{\max}(S)tr(P) \qquad (13)$$

Using (12) and (13) in (11) yields

$$tr(P_i)\le -\frac{tr(\eta_i)}{2\lambda_{\min}(S_{CLi})} \qquad (14)$$

Given the difficulty to find the positive scalars η_i , we can search with LMIs software for the upper bounds on time derivatives of $\dot{V}_i(x)$ for each model. Once η_i is found, Theorem 2.2 is held. ■

3. STABILIZABILITY OF SOFT SWITCHING SIGNALS FOR DISCRETE-TIME

Equations (3), (4) and (5) can be combined to obtain the closed loop state transition matrix for the plant model:

$$A-BK=\sum_{i=1}^{N}\mu_i\left(A_i+B_iK_i\right)=\sum_{i=1}^{N}\mu_i A_{CLi} .$$

Therefore, similarly, we have the closed-loop equations:

$$x(k+1)=\sum_{i=1}^{N}\mu_i A_{CLi}x(k) \qquad (15)$$

$$z(k)=Cx(k) \qquad (16)$$

As indicated in [2], even if each of matrices A_{CLi} is globally stable, there can exist a switching sequence that destabilizes the closed-loop dynamics. For all given stable matrices A_{CLi} , the stability of the soft switching system is guaranteed if we can find out a common Lyapunov matrix P.

Theorem 3.1: *The soft switching systems for the stable closed-loop state matrices A_{CLi} in (15) can guarantee the global asymptotical stability for any switching sequence with any plant model if there exists a common positive symmetric definite matrix $P>0$ and a scalar $\gamma>0$ such that* $\begin{bmatrix} P & PA_{CLi}^{'} & \gamma\\ A_{CLi}P & P & 0\\ \gamma & 0 & \gamma I\end{bmatrix}>0,\ \forall i$.

Proof: For the stable discrete time systems, we always have the Lyapunov function decreasing $V_i(k)=x^{'}(k)Px(k)$ and $V_i(k+1)-V_i(k)<0$, and the systems are stable for any soft switching sequence with any plant model since they share a common Lyapunov matrix P:

$$V_i(k+1)-V_i(k)=\left(\sum_{i=1}^{N}\mu_i A_{CLi}x\right)' P\left(\sum_{i=1}^{N}\mu_i A_i x\right) \\ -xPx<0 \to A_{CLi}PA'_{CLi}-P<0 \tag{17}$$

By adding a scalar $\gamma>0$ in (17), we have $P-A'_{CLi}PA_{CLi}-\gamma I>0$, or $P-(A'_{CLi}P)P^{-1}(PA_{CLi})-(\gamma)I\gamma^{-1}(\gamma)>0$. By using Schur complement, this equation is equivalent to the LMI in Theorem 3.1. Hence, the common Lyapunov matrix in Theorem 3.1 is the solution to the following LMI:

$$\underset{P>0,\ \gamma>0}{\text{Min}}\ \gamma\text{, subject to}\begin{bmatrix} P & PA'_{CLi} & \gamma \\ A_{CLi}P & P & 0 \\ \gamma & 0 & \gamma I\end{bmatrix}>0,\quad \forall i\ .\ \blacksquare$$

Example 3.1. This example is taken in [16]: Consider the following discrete hybrid model set: $\Omega=\{[A_1,B_1,C_1],[A_2,B_2,C_2]\}$ with $A_1=\begin{bmatrix}0.90 & -0.80\\ 0.30 & 0.80\end{bmatrix}$, $B_1=\begin{bmatrix}0.20\\ 0.20\end{bmatrix}$, $A_2=\begin{bmatrix}0.85 & -0.75\\ 0.35 & 0.75\end{bmatrix}$ $B_2=\begin{bmatrix}0.10\\ 0.10\end{bmatrix}$, and $C_1=C_2=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$. Applying the linear quadratic feedback as described in [16] and solving directly with LMIs, we can find out a common Lyapunov mantrix for this model set: $P=\begin{bmatrix}3.3611 & 0.2859\\ 0.2859 & 1.2163\end{bmatrix}>0$. Then this hybrid system is globally asymptotically stable for any switching sequence with any plant model. Suppose that the real plant model has $\mu_1=\mu_2=0.5$; and the initial state is $x_0=\begin{bmatrix}1\\ 1\end{bmatrix}$. Fig. 2 shows the performance of the linear quadratic feedback using the above common Lyapunov matrix.

The difference $V(k+1)-V(k)$ in (17) involves many cross matrices from $A_{CLi}PA'_{CLi}-P<0$. In this paper we do not analyze the necessary conditions that guarantee the stability of the discrete closed loop switching signals. Instead, we look at $A_{CLi}A'_{CLi}$. If $\lambda_{\max}(A_{CLi}A'_{CLi})<1$, the closed loop system is strictly stable since we always have $\frac{x'(A_{CLi}A'_{CLi})x}{x'x}\le\lambda_{\max}(A_{CLi}A'_{CLi})$.

Then,

$$V_i(k+1)-V_i(k)=x'(A_{CLi}PA'_{CLi})x-x'Px \\ \to \lambda_{\max}(A_{CLi}A'_{CLi})-I<0. \tag{18}$$

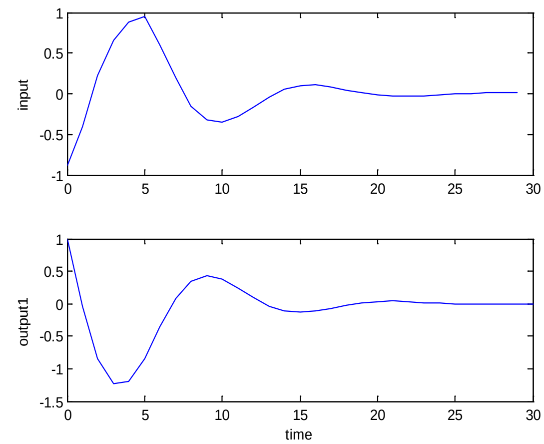

Fig. 2: The system is stable for the real model of $\mu_1=\mu_2=0.5$

The closed loop state feedback A_{CLi} is strictly stable. Now we use the above notion to prove a new stabilizability condition for the soft switching systems of the discrete-time case.

Theorem 3.2: *The soft switching systems for the hybrid discrete-time case in (15) and (16) can guarantee the global asymptotical stability for any switching sequence with any plant model if* $\lambda_{\max}(A_{CLi}A'_{CLi})<1$, $\forall i$.

Proof: We have:

$$\dot V(x)=\sum_{i=1}^{N}\mu_i\dot V_i(x)=\sum_{i=1}^{N}\mu_i\left(V_i(k+1)-V_i(k)\right) \\ =\sum_{i=1}^{N}\mu_i\left(x'(A_{CLi}P_iA'_{CLi})x-x'P_ix\right)<0 \tag{19}$$

For all given stable matrices A_{CLi}, the stability of the switching systems is guaranteed if we can find out a common Lyapunov matrix P. Here we have selected the common Lyapunov matrix $P=I$ and equation (19) can be transformed as:

$$\frac{1}{x'x}\dot V(x)=\sum_{i=1}^{N}\mu_i\left(\frac{x'(A_{CLi}A'_{CLi})x}{x'x}-I\right)<0 \tag{20}$$

Since we always have $\frac{x'(A_{CLi}A'_{CLi})x}{x'x}\le\lambda_{\max}(A_{CLi}A'_{CLi})<1$. Then equation (20) is always held and the soft switching systems are of global asymptotical stability for any switching sequence with any plant model. ■

4. CONCLUSIONS

In this paper, we have considered the stability and stabilizability of soft switching systems for polytopic uncertainties via their stable closed-loop state feedback for the continuous-time and the discrete-time hybrid systems. Some new stabilizability conditions of soft switching signals are presented.

Due to the knowledge limitation, we just show some necessary conditions for the stabilizability of the closed loop state feedback but we do not provide general stabilizing switching laws for hybrid multiple model controllers. Additionally, we have not considered the hybrid multiple model controllers subject to constraints and disturbances.

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