Switched Fuzzy Systems: New Directions for Intelligent Control and Decision

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Abstract—A summarized study of the current state-of-the-art of the controlled intelligent systems based on the synergy of the potential of fuzzy logic in Takagy-Sugeno fuzzy systems with the structural flexibility and sustainability of switched nonlinear dynamic systems. In particular, following some of the fundamental theorems on quadratic stability of general nonlinear dynamic systems, due to Zhao and Dimirovski (2004), novel stability results have been derived. Thus it was also feasible do derive novel synthesis design solutions for intelligent decision and control task problems based on the switched fuzzy systems theory and Lyapunov stability theory.

Keywords—decision and control; fuzzy systems; intelligence forms; inference capacity; Lyapunov stability theory; nonlinear dynamic systems; switched systems; synergy of fuzzy and switched systems.

I. INTRODUCTION

The large class of switched hybrid systems has attracted extensive research during the last couple of decades both as such and also in conjunction of the even larger class of hybrid systems, e.g. see [2], [8], [13], [14], and [22]. For, these systems have a wide range of potential applications. For instance, such systems are widely used in the multiple operating point control systems, the systems of power transmission and distribution, constrained robotic systems, intelligent vehicle highway systems, etc.

Basically, a switched system consists of a family of dynamic continuous-time (or discrete-time subsystems) and a switching rule law that governs and orchestrates the switching among them.

Recently switched systems have been extended further to encompass switched fuzzy systems too [12], [14], [20] following the advances in fuzzy sliding mode control [4], [9], [11]. Though for long time it was well known the ideal relay switching is a time optimal control law [17]. A switched fuzzy system involves fuzzy systems among its subsystems. This extension emanated out of the remarkable developments in theory, applications, and the industrial implementations of fuzzy control systems, e.g. see [1], [16], [18], [19], and [24].

However, it was due to employing the crucial role of Lyapunov stability theory as appropriate within the context of fuzzy systems, e.g. such as of Takagi-Sugeno type, which are essentially nonlinear dynamic systems. For, only then it was feasible to develop compatible synergy of switched systems and fuzzy systems into the class of switched-fuzzy systems that possesses the potential of generating a kind of intelligent system operation under appropriate synthesis of decision and control feedback.

II. CLASSES OF SYSTEMS INVOLVED

Consider the definition of general dynamic systems and the respective decision and control infrastructure form the viewpoint of Engineering Cybernetics.

Fig. 1. An illustration of the background context of decision and control for general dynamic systems in consistence with the fundamental natural laws, which is implemented within the control, decision and management infrastructure.

It is important to notice that, at a given fixed instant of time, the values of control input, state-transition and output measurement vectors become real-valued vectors in the respective Euclidean spaces regardless to which classes of functional spaces they may belong. Thus it is definition fully consistent with the natural laws on energy and mass in consistence with the third fundamental quantity of information. This is to say, natural motion under driving momentum or force-driven evolution dynamics.
Consider the continuous fuzzy model that involves rules of the type as follows:

\[ R^l_{\sigma(t)}: \text{If } \xi_1 \text{ is } M^l_{\sigma(t)} \text{ and } \xi_p \text{ is } M^l_{\sigma(t)p}, \]

Then \[ \dot{x} = A_{\sigma(t)}x(t) + B_{\sigma(t)}u_{\sigma(t)}(t) \]

where \[ \sigma: R_t \rightarrow M = \{1, 2, \cdots, m\} \]

is a piecewise constant function that is representing the switching signal.

In rule-based model above, symbols denote:
- \( R^l_{\sigma(t)} \) denotes the \( l \)-th fuzzy inference rule,
- \( N_{\sigma(t)} \) is the number of inference rules,
- \( u(t) \) is input variable, and
- \( x(t) = [x_1(t) \ x_2(t) \ \cdots \ x_N(t)]^T \in R^m \) represents the vector of state variables.
- \( \xi = [\xi_1 \ \xi_2 \ \cdots \ \xi_p] \) represents the vector of the rule’s antecedent variables.

In the linear dynamic model of the rule’s consequent, the matrices \( A_{\sigma(t)} \in R^{m \times m} \) and \( B_{\sigma(t)} \in R^{m \times p} \) are assumed to have the appropriate dimensions.

The \( i \)-th fuzzy subsystem thus can be represented as follows:

\[ R^i : \text{If } \xi_1 \text{ is } M^i_1 \text{ and } \xi_p \text{ is } M^i_p, \]

Then \[ \dot{x}(t) = A_ix(t) + B_iu_i(t) \]

For all \( l = 1, 2, \ldots, N_i; \quad i = 1, 2, \ldots, m. \)

Thus the overall model of the \( i \)-th fuzzy sub-system is described by means of the equation

\[ \dot{x}(t) = \sum_{i=1}^{N_i} \eta_i(\xi(t))(A_ix(t) + B_iu_i(t)) \]

along with

\[ \eta_i(t) = \frac{\prod_{l=1}^{i-1} \mu_{\xi_l}(t)}{\sum_{l=1}^{i} \mu_{\xi_l}(t)}, \quad 0 \leq \eta_i(t) \leq 1, \quad \sum_{i=1}^{N_i} \eta_i(t) = 1 \]  

(5-a,b)

In the above model (3)-(5), the symbol \( \mu_{\xi_l}(t) \) denotes the membership function of the fuzzy state variable \( x_p \) that belongs to fuzzy subset \( M^l_p \).

III. ISSUES AND TASK PROBLEMS DISCUSSED

A. Stability Considerations for Intelligent Switched Fuzzy-Systems

III.A.1/. Certain fundamental theorems for switched nonlinear dynamic systems.

III.A.2/. Novel stability results for switched fuzzy-systems.

III.A.3/. Possible extension to the framework of discrete-time dynamic systems.

B. Combined Stat/Output Feedback Control and Arbitrary Switching

III.B.1/. Combining state-feedback controls with switching among fuzzy sub-systems.

III.B.2/. Combining output-feedback controls with switching among fuzzy sub-systems.

III.3/. Possible extension to the framework of discrete-time dynamic systems.

C. Combined Stat/Output Feedback Control and Arbitrary Switching

III.C.1/. Illustrative example 1 and comment on the respective simulation results.

III.C.2/. Illustrative example 2 and comment on the respective simulation results.

III.C.3/. Some additional observations.

IV. CONCLUDING REMARKS AND FUTURE RESEARCH

you begin to format your paper, first write and save the content as a separate text file. Keep your text and graphic files separate until after the text has been formatted and styled. Do not use hard tabs, and limit use of hard returns to only one return at the end of a paragraph. There are several aspects and issues that are believed worth addressing as concluding remarks and, subsequently, discussed within the prospect of future potential developments.

Firstly the innovated representation model for the class of switched fuzzy systems, in continuous-time setting, also extendable to the discrete-time one, is to be noticed.

Secondly, the new sufficient conditions for quadratic asymptotic stability of the control system with the given switching laws (new theorems) via the common Lyapunov function approach are particularly important to rely on. (Following these new stability results, only the stability of a certain combination of subsystem matrices has to be checked, which is considerably easier to carry out.

Finally, appropriate stabilizing switching laws in the state-variable dependent form have been synthesized for both fuzzy switched systems even without additional state or output feedback controls.