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NETWORKED CONTROL SYSTEMS DESIGN CONSIDERING SCHEDULING RESTRICTIONS AND LOCAL FAULTS USING LOCAL STATE ESTIMATION

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Abstract. *Nowadays, Network Control Systems represent a common solution when solving connectivity issues for distributed control systems. However, this approach tends to increase time complexity in terms of time delays, and thus, making necessary the study of behavior of such time delays as well as local structure and the differential equations which model such a behavior. Time delays need to be known a priori, but from a dynamic, real-time behavior. To do so, this paper presents the use of a dynamic, priority exchange scheduling for bounding time delays. The objective is to show how to tackle multiple time delays, as well as faults that produce variable structure onto dynamic model and the dynamic response from real-time scheduling approximation. The novelty of this approach is to use both, the appearance of faults and time delays, as perturbations considering nonlinear behavior through a fuzzy TKS approach with local observer for multiple state estimation, in a codesign strategy. The related control law is designed considering fuzzy logic for nonlinear time delays coupling and inherent local fault appearance.*
Keywords: Fuzzy systems, Network control systems, State estimation

1. Introduction.

Real-time restrictions are the most certain time constraints when the behavior of a system tends to be periodic and repeatable. Considering this, the control design and stability analysis of Network Control Systems (NCSs) have been studied, in which a key scheduling restriction is the effect of the network-induced delays in the NCS performance. This delay can be constant, time-varying, or even random, depending on the scheduler, network type, architecture, operating systems, etc. Further, when a local fault occurs during the operation of an NCS, a respective local fault tolerance strategy has to be applied. Nevertheless, applying such a fault tolerance strategy impacts the overall performance of the NCS, since dynamic conditions are modified. Therefore, it seems necessary to take into account current local conditions, in order to keep NCS performance, even if it is degraded.

Example 1.1. *Let us suppose a general NCS. Different local faults may simultaneously occur during its operation. Normally, due to the distributed nature of the NCS, these faults are locally tackled using a scheduling algorithm, which introduces time delays due* *to the local recuperation strategies that, for safety reasons, may be bounded to a maximum allowable transfer interval (MATI) [18].*

Hence, the local application of the scheduling algorithm is needed for the partial recovery of the NCS, but this implies that the overall performance of the NCS is now degraded. Given this, a solution may be to model each bounded time delay due to each local fault as well as the local impact of the fault itself. Based on this simple idea, it is possible to model the global and non linear effects of the time delays, in order to propose each time a controller that results adequate given each particular situation.

This paper proposes a novel codesign strategy, considering bounded time delays and variable structure for NCSs. Codesign implies the concurrent development of both, hardware and software components [3]. The use of codesign here attempts to improve the main advantages of NCSs, such as their low cost, small volume of wiring, distributed processing, simple installation, maintenance, and reliability [2]. In this codesign strategy, an NCS is *reconfigured* according to bounded time delays.

Definition 1.1. *Reconfiguration is defined as a transition that modifies the structure of a system so it changes its representation of states [14].*

Reconfiguration is used here as a feasible approach for modifying time delays, as well as taking into account local fault conditions (such as sensor faults), in order to maintain the performance of the NCS. It is necessary to represent a nonlinear NCS with these two key characteristics: time delays (bounded by a scheduler algorithm) and the appearance of local faults developing onto variable structure. Thus, in this paper, time delays and the appearance of local faults are taken to develop a fuzzy model of the controller, capable of solving this nonlinear behavior. This control approach is feasible, since local faults are known as well as bounded time delays.

The focus of this paper is to produce a methodology for networked control systems during time variant delays and modification of state space representation as state estimation having as challenge loosing states locally during the presence of local faults. The novelty of this work is based upon time delay modeling by using scheduling analysis in terms of variable structure due to appearance of local faults and the related loss of dropped variables. This work focused the reader onto the need of integration amongst local faults appearance, bounded time delays and loss of consistent structure either local or global.

Here, the structure is modified according to fault appearance; therefore, augmented states are a suitable strategy for accomplishing system representation. In order to propose the augmented states, the use of an observer is pursued specifically by using a Luenberg Observer. It is expected that some of the states will not be available since local faults make the whole state non-observable. Therefore, the structure is modified as a consequence following the implementation of an observer as proposed by [20].

2. **Related Work.**

In control systems, several modeling strategies for managing time delays within control laws have been studied by different research groups.

Example 2.1. *[13] proposes the use of a time delay scheme integrated to a reconfigurable control strategy, based on a stochastic methodology. [9] describes how time delays are used as uncertainties, which modify pole placement of a robust control law. [8] presents an interesting case of fault tolerant control approach related to time delay coupling. [5] studies reconfigurable control from the point of view of structural modification, establishing a logical relation between dynamic variables and the respective faults. Finally, [1,17] consider that reconfigurable control strategies perform a combined modification of system structure and dynamic response, and thus, this approach has the advantage of bounded modifications over system response even when the system structure is modified.*

Further work has been presented by [15] where decentralized control is presented where variable structure is reviewed as a design strategy for a number of situations.

Regarding NCS, [13] also analyzes several important facets of NCSs, by introducing models for the delays in NCS: first as a fixed delay, then as an independently random, and finally, like a Markov process. Optimal stochastic control theorems for NCSs are introduced, based upon the independently random and Markovian delay models. [18] introduces static and dynamic scheduling policies for transmission of sensor data in a continuous-time LTI system. They introduce the notion of the *maximum allowable transfer interval* (*MATI*). This is the longest time after which a sensor should transmit a data. They also derive bounds of the MATI, such that NCS is kept stable. This MATI ensures that the Lyapunov function of the system under consideration is strictly decreasing at all times. [22] extends the work of [18], developing a theorem which ensures the decrease of a Lyapunov function for a discrete-time LTI system at each sampling instant, by using two different bounds. These results are less conservative than those of Walsh, since here it is not required that the system Lyapunov function should be strictly decreasing at all time. Further, a number of different linear matrix inequality (LMI) tools for analyzing and designing optimal switched NCSs are introduced. Alternatively [23] takes into consideration both the network-induced delay and the time delay in the plant, and thus, introduces a controller design method, using the delay-dependent approach. An appropriate Lyapunov functional candidate is used to obtain a memoryless feedback controller, derived by solving a set of Linear Matrix Inequalities (LMIs). [19] models the network induced delays of the NCSs as interval variables governed by a Markov chain. Using the upper and lower bounds of the delays, a discrete-time Markovian jump system with norm-bounded uncertainties is presented to model the NCSs. Based on this model, an H_∞ state feedback controller can be constructed via a set of LMIs. Recently, [7] introduces a new (descriptor) model transformation for delay-dependent stability, for systems with time-varying delays in terms of LMIs. It also refines recent results on delay-dependent H_∞ control, and extends them to the case of time-varying delays.

All these previous works have significance to understand how to treat the time delays, regardless of their nature, as well as the impact of local faults. Based upon this review, this paper presents a model that integrates the time delays for a class of nonlinear system and a fuzzy control for NCSs [14,16,22], considering time delays induced by the computer network as a result of online reconfiguration. This modeling approach is presented to bound time delays from computing behavior and taking local faults as a key issue, enhancing this modeling approximation. Also, the stability analysis is revised as well.

Here the use of LMI is pursued since local variable structure is presented. The proposed approximation uses Fuzzy Takagi Sugeno representation in order to delimited local variable structure of the model guarantee stability.

3. **Scheduling Approach.** The objective here is to present a reconfiguration control strategy developed from the time delay knowledge, following scheduling approximation where time delays are known and bounded according to used scheduling algorithm. The scheduling strategy proposed here and reviewed by [3,4] pursues to tackle local faults in terms of fault tolerance. In this situation, current time delays would be inevitable.

Classical Earliest Deadline First (EDF) plus Priority Exchange (PE) algorithm are used here to decompose time lines and the respective time delays when present. For instance, time delays are supervised for a number of tasks as follows:

$$c_1 \rightarrow c_n \quad T_1 \rightarrow T_n \tag{1}$$

Priority is given as the well known EDF algorithm, which establishes that the process with the closest deadline has the most important priority [11]. However, when an aperiodic task appears, it is necessary to deploy other algorithms to cope with concurrent conditions. To do so, the PE algorithm is used to manage spare time from the EDF algorithm. The PE algorithm [6] uses a virtual server that deploys a periodic task with the highest priority in order to provide enough computing resources for aperiodic tasks. This simple procedure gives a proximity, deterministic, and dynamic behavior within the group of included processes. In this case, time delays can be deterministic and bounded.

Example 3.1. *Consider a group of tasks as shown in Table 1. In this case, consumption times as well as periods are given in terms of integer units. Remember: the server task is the time given for an aperiodic task to take place on the system.*

TABLE 1. First example for PE algorithm

Name	Consumption (in units)	Period (in units)
Task 1	2	9
Task 2	1	9
Task 3	2	10
Server	1	6

The result of the ordering based upon PE is presented in Figure 1.

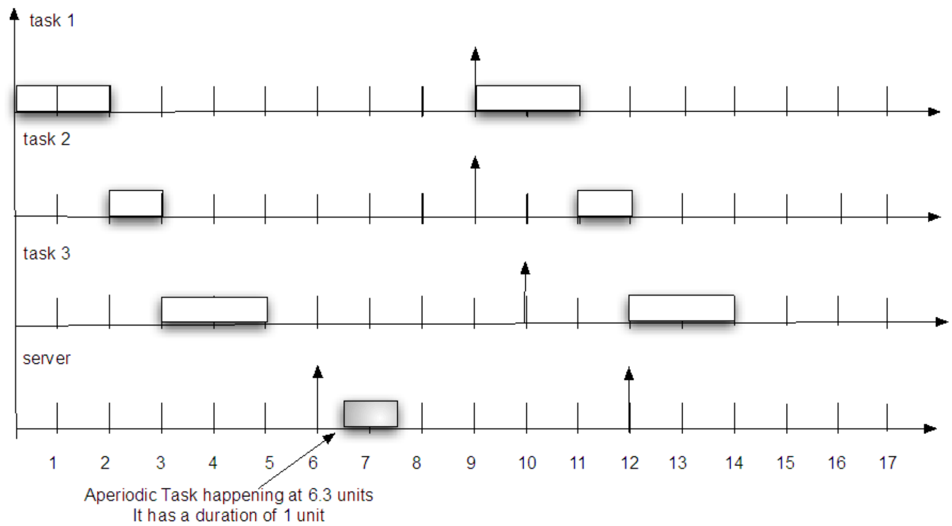

FIGURE 1. Related organization for PE of tasks in Table 1

Based on this dynamic scheduling algorithm, time delays are given as current calculations in terms of task ordering. In this case, every time that the scheduling algorithm takes place, the global time delays are modified in the short and long term. This scheduling algorithm is invoked every fault scenario by allocating non periodic tasks to overcome this situation.

Example 3.2. *For instance, consider the following example, in which four tasks are set, and two aperiodic tasks take place at different times, giving different events with different time delays.*

The following task ordering is shown in Figure 2, using the PE algorithm, where clearly time delays appear.

TABLE 2. Second example of PE

Name	Consumption (in units)	Period (in units)
Task 1	2	9
Task 2	1	9
Task 3	2	10
Server	1	6
Aperiodic task 1 (ap1)	0.9	It occurs at 9
Aperiodic task 2 (ap2)	1.0	It occurs at 13

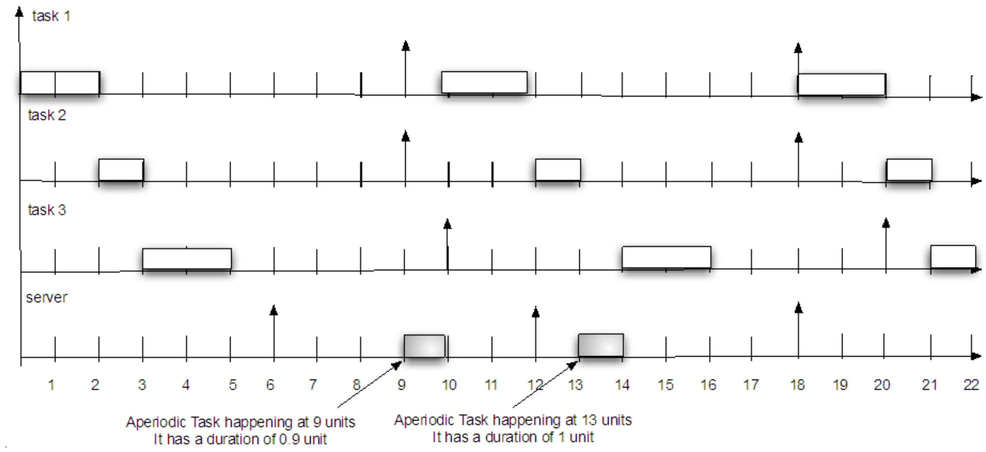

FIGURE 2. Task organizations considering the second example for the PE algorithm

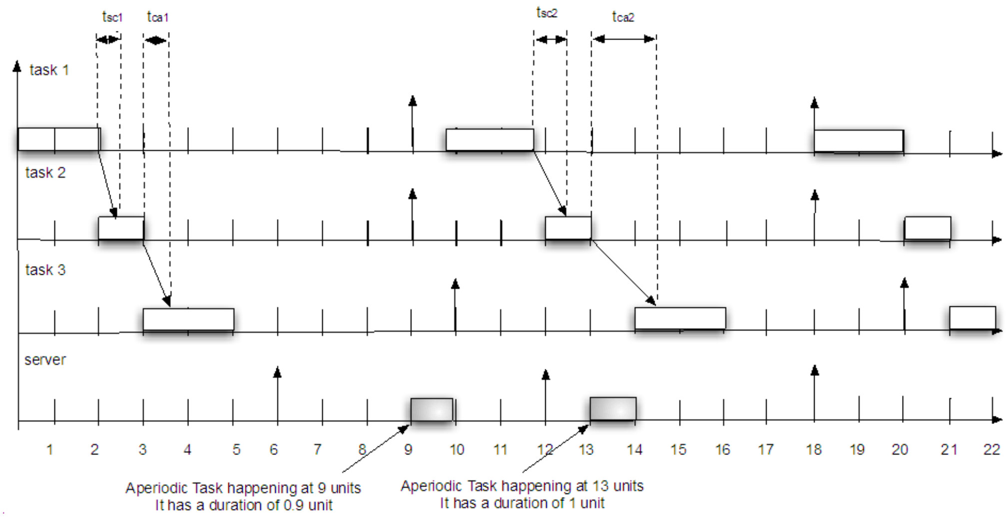

FIGURE 3. Related time delays are depicted according to both scenarios.

Now, from this, a resulting ordering of these tiny time delays is given for two scenarios, as shown in Figure 3.

These two scenarios present two different local time delays that need to be taken into account before hand, in order to settle the related delays according to scheduling approach and control design. These time delays can be expressed in terms of local relations between both dynamical systems. These relations are the actual and possible delays, bounded as marked limits of possible and current scenarios. Then, delays may be expressed as local summations with a high degree of certainty.

Example 3.3. *In this last example, during the second scenario, a total delay is given as:*

Total delay = *consumption_time_delay_aperiodic_task 1*
+ *consumption_time_delay_task 1* + *tsc2*
+ *consumption_time_delay_task 2*
+ *consumption_time_delay_aperiodic_task 2*
+ *consumption_time_delay_task 3*

Now, from this example, l_p is equal to 2 (*consumption_time_delay_aperiodic_task* 1 + *consumption_time_delay_task* 1 + *tsc*2 + *consumption_time_delay_task* 2) and l_c is equal to 3 (*consumption_time_delay_aperiodic_task* 2 + *consumption_time_delay_task* 3). l_p and l_c are the total number of local delays within one scenario from sensor to control and from control to actuator respectively. l_p and l_c are used as limits of current delays per scenario as shown in Equations (8) and (9). These limits are modified according to the allowed scenario that guarantees schedulability during online process; nevertheless, this execution needs to be bounded by the only considered scenarios from TKS modelling.

4. **Fuzzy Control Design Considering Time Delays and Local Faults.** Having defined time delays as a result of a scheduling approximation as well as local faults considering sensor faults (just local and bounded faults are bounded), several scenarios are potentially presented following this time delay behavior. In fact, the number of scenarios is finite, since the combinatorial formation is bounded. Therefore, any strategy in order to design a control law needs to take into account gain scheduling approximation. To do so, a fuzzy control strategy based upon Takagi-Sugeno is applied. Based on fuzzy control systems (Mendez-Monroy *et al.*, 2009) considering variable structure system representation it stays as:

$$u_{i,j}(x_i(t)) = e^{-\left(\frac{x_i - c_{ij}}{\sigma_{ij}}\right)^2} \qquad 1 \to i \to m \text{ and } 1 \to j \to m \tag{2}$$

where x_i are the states, m is the number of inputs and μ is the related membership function. Thus:

$$g_i = \Pi_{i=1}^{m}\{u_{ij}[x_i(k)]\} \tag{3}$$

$$h_j = \frac{g_j}{\sum_{j=1}^{m} g_j} \tag{4}$$

$$X(k+1) = \sum_{j=1}^{m} \left[h_j \left\{A_j^p x(k) + B_j^p u(k)\right\}\right] \tag{5}$$

and A_j^p and B_j^p are the plant representation per scenario according to current time delays following Figure 4, and ρ_j is the relation of fault vector even considering local variable structure when faults occurs.

Now let t_{caj} be the current time delay from controller to actuator, and t_{scj} be the current time delay from sensor to controller, that are defined as in previous section considering total time delay definitions and ρ_j^p and ρ_j^c be the relations of fault presence through the event, where it represents local variable structure.

$$x_p(k+1) = \sum_{j=1}^{m} \left[h_j \left\{A_j^p x_p(k) + \rho_j^p B_j^p u_p(k - t_{caj})\right\}\right] \tag{6}$$

$$x_c(k+1) = \sum_{j=1}^{m} \left[h_j^p \left\{A_j^c x_c(k) + \rho_j^c B_j^c u_c(k - t_{scj})\right\}\right] \tag{7}$$

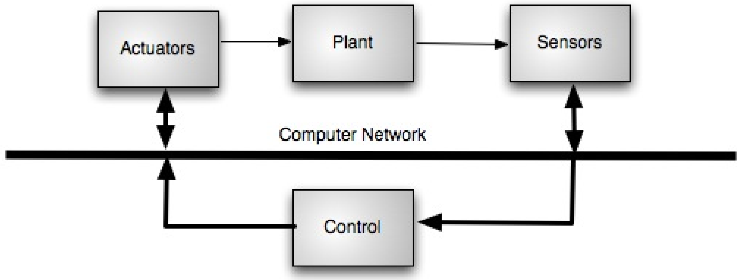

FIGURE 4. Network control system diagram

From [14], the time delay representation in terms of discrete view is:

$$B_j^p = \sum_{i=1}^{l_p} \left[\int_{t_i}^{t_{i+1}} \rho_j^c B_j^c e^{A_j^c t} dt \right] \tag{8}$$

$$B_j^c = \sum_{i=1}^{l_c} \left[\int_{t_i}^{t_{i+1}} \rho_j^p B_j^p e^{A_j^p t} dt \right] \tag{9}$$

Remember from last section that l_c and l_p are the total number of local time delays that appear per scenario and are the source of t_{scj} and t_{caj} respectively:

$$y_{p_i} = c_p^i x_p(k)$$
$$y_{c_i} = c_c^i x_c(k)$$

and the outputs are gathering as:

$$y_p = \sum_{j=1}^{m} \left[h_j \{ c_p^j x_p(k) \} \right] \tag{10}$$

$$y_c = \sum_{j=1}^{m} \left[h_j \{ c_c^j x_c(k) \} \right] \tag{11}$$

$$u_p(k - t_{caj}) \to y_c = c_c x_c(k) \tag{12}$$

$$u_c(k - t_{scj}) \to y_p = c_p x_p(k) \tag{13}$$

$$x_p(k+1) = \sum_{j=1}^{m} \left[h_j \{ A_j^p x_p(k) + \rho_j^p B_j^p u(k - t_{caj}) \} \right] \tag{14}$$

$$= \sum_{j=1}^{m} \left[h_j \{ A_j^p x_p(k) + \rho_j^p B_j^p c_c x_c(k - t_{caj}) \} \right] \tag{15}$$

From last equation, the related dynamics are expressed as A_j^c, B_j^c, and C_c^j, where j is the index with respect to each scenario. In terms of augmented states considering, the estimated states are presented as observer since local variable structure is used when local fault appears. In this case, fault event disrupts the error as well as time delays; moreover, this event modifies local structure onto time as overall situation. Although ρ_j^* states a missing state in terms of either plant or controller. The proposal of current group of observers is to guarantee system structure; therefore, stability in terms of time delays and misleading structure should be accomplished. The related observers states are presented as $z(k)$. In this case H_j^p f_j^p k_j^p T_j^p are the observer parameters to be defined.

$$x_p(k+1) = \sum_{j=1}^{m} \left[h_j \left\{ A_j^p x_p(k) + \rho_j^p B_j^p \left\{ \sum_{i=1}^{m} h_j (c_c^i x_c(k - t_{cai})) \right\} \right\} \right]$$

$$\begin{bmatrix} x_p(k+1) \\ z(k+1) \\ \hat{x}_p(k+1) \end{bmatrix} = \sum_{j=1}^{m} \begin{bmatrix} h_j \left[A_j^p \begin{bmatrix} x_p(k) \\ \hat{x}_p(k) \end{bmatrix} + \sum_{i=1}^{m} h_i \rho_j^p B_j^p (c_c^i x_c(k - t_{cai})) \right] \\ f_j^p z(k) + k_j^p \left(c_j^p \begin{bmatrix} x_p(k) \\ \hat{x}_p(k) \end{bmatrix} + T_j^p B_j^p \sum_{i=1}^{m} (h_i c_c^i x_c(k - t_{cai})) \right) \\ z(k) + H_j^p z(k) \end{bmatrix} \tag{16}$$

Re-ordering last equation

$$\begin{bmatrix} x_p(k+1) \\ \hat{x}_p(k+1) \\ z(k+1) \end{bmatrix} = \sum_{j=1}^{m} \begin{bmatrix} h_j \left[A_j^p \begin{bmatrix} x_p(k) \\ \hat{x}_p(k) \end{bmatrix} + \sum_{i=1}^{m} h_i \rho_j^p B_j^p (c_c^i x_c(k - t_{cai})) \right] \\ z(k) + H_j^p z(k) \\ f_j^p z(k) + k_j^p \left(c_j^p \begin{bmatrix} x_p(k) \\ \hat{x}_p(k) \end{bmatrix} + T_j^p B_j^p \sum_{i=1}^{m} (h_i c_c^i x_c(k - t_{cai})) \right) \end{bmatrix}$$

Re-organizing these sums

$$\begin{bmatrix} x_p(k+1) \\ \hat{x}_p(k+1) \\ z(k+1) \end{bmatrix} = \sum_{j=1}^{m} \sum_{i=1}^{m} \begin{bmatrix} h_j \left[A_j^p \begin{bmatrix} x_p(k) \\ \hat{x}_p(k) \end{bmatrix} + h_i \rho_j^p B_j^p (c_c^i x_c(k - t_{cai})) \right] \\ z(k) + H_j^p z(k) \\ f_j^p z(k) + k_j^p \left(c_j^p \begin{bmatrix} x_p(k) \\ \hat{x}_p(k) \end{bmatrix} + T_j^p B_j^p (h_i c_c^i x_c(k - t_{cai})) \right) \end{bmatrix}$$

Now in terms of the controller:

$$x_c(k+1) = \sum_{i=1}^{m} \left[h_i \left\{ A_i^c x_c(k) + \rho_i^c B_i^c u_c(k - t_{sci}) \right\} \right] \tag{17}$$

Now in terms of augmented states due to local faults and the related closed loop.

$$x_c(k+1) = \sum_{i=1}^{m} \left[h_i \left\{ A_i^c x_c(k) + \rho_i^c B_i^c \left(\sum_{j=1}^{m} h_j c_p^j \begin{bmatrix} x_p(k - t_{scj}) \\ \hat{x}_p(k - t_{scj}) \end{bmatrix} \right) \right\} \right]$$

Re-ordering

$$x_c(k+1) = \sum_{i=1}^{m} \sum_{j=1}^{m} \left[h_j A_j^c x_c(k) + \rho_j^c B_j^c h_j c_p^i \begin{bmatrix} x_p(k - t_{sci}) \\ \hat{x}_p(k - t_{sci}) \end{bmatrix} \right] \tag{18}$$

Now, integrating both plant and control states with the observer states leads to the following configuration

$$\begin{bmatrix} x_p(k+1) \\ \hat{x}_p(k+1) \\ z(k+1) \\ x_c(k+1) \end{bmatrix} = \sum_{j=1}^{m} \sum_{i=1}^{m} \begin{bmatrix} h_j A_j^p \begin{bmatrix} x_p(k) \\ \hat{x}_p(k) \end{bmatrix} + h_j h_i \rho_j^p B_j^p (c_c^i x_c(k - t_{cai})) \\ z(k) + H_j^p z(k) \\ f_j^p z(k) + k_j^p c_j^p \begin{bmatrix} x_p(k) \\ \hat{x}_p(k) \end{bmatrix} + k_j^p T_j^p B_j^p h_i c_c^i x_c(k - t_{cai}) \\ h_i A_i^c x_c(k) + \rho_i^c B_i^c h_i c_p^j \begin{bmatrix} x_p(k - t_{scj}) \\ \hat{x}_p(k - t_{scj}) \end{bmatrix} \end{bmatrix}$$

For x_p:

$$x_p(k+1) = \sum_{j=1}^{m} \left[h_j \left\{ A_j^p x_p(k) + \sum_{i=1}^{m} h_i \rho_j^p B_j^p (c_c^i x_c(k - t_{cai})) \right\} \right] \tag{19}$$

$$x_p(k+1) = \sum_{j=1}^{m} \sum_{i=1}^{m} \left[h_j h_i [\rho_j^p B_i^p (c_c^i x_c(k - t_{cai}))] + h_j A_j^p x_p(k) \right] \tag{20}$$

For x_c:

$$x_c(k+1) = \sum_{j=1}^{m} \left(h_j \left\{ A_j^c x_c(k) + h_i \rho_j^c B_j^c \left(\sum_{j=1}^{m} h_j (c_p^i x_p(k - t_{scj})) \right) \right\} \right) \tag{21}$$

$$x_c(k+1) = \sum_{j=1}^{m} \sum_{i=1}^{m} \left[h_j h_i \left[\rho_j^p B_j^p (c_c^j x_c(k) + h_i \rho_j^c B_i^c (h_j (c_p^i x_p(k - t_{scj})))) \right] \right] \tag{22}$$

Now, as augmented states:

$$X = \begin{bmatrix} x_c \\ x_p \end{bmatrix} \tag{23}$$

$$\begin{matrix} x_c(k+1) \\ x_p(k+1) \end{matrix} = \begin{cases} \sum_{j=1}^{m}\sum_{i=1}^{m}\left[h_j h_i[\rho_j^p B_j^p(c_c^i x_c(k-t_{cai}))] + h_j A_j^p x_p(k)\right] \\ \sum_{j=1}^{m}\sum_{i=1}^{m}\left[(h_j h_i[\rho_j^c B_j^c(c_p^i x_p(k-t_{sci}))] + h_j A_j^c x_c(k))\right] \end{cases} \tag{24}$$

Here, the delays are independent based upon the time obtained from scheduling approximation:

$$t_{ca1} + t_{sc1} < t_{ca2} + t_{sc2} < \cdots < t_{cam} + t_{scm} < T \tag{25}$$

Now, the observer design is defined as follows, in this case error is stated as $e(k+1)$ whereas A, B and C are the related local plant dynamics where it is the observer gain defined through two auxiliary values k_1 and k_2.

$$\begin{aligned} e(k+1) = {} & (A - HCA - k_1C)e(k) + (F - (A - HCA) - k_1C)z(k) \\ & + [k_2 - (A - HCA - k_1C)H]y(k) \\ & + [T - (I - HC)]Bu(k) + (HC - I)Ed \end{aligned} \tag{26}$$

$$k = k_1 + k_2$$

$$(HC - I)E = 0 \tag{27}$$

$$T = (I - HC) \tag{28}$$

$$f = A - HCA - k_1C \tag{29}$$

$$k_2 = fH$$

An important value and condition is related to both ranks

$$rank(CE) = rank(E) \tag{30}$$

One of the important conditions for this early approximation is that Lyapunov candidate function should be expressed as equilibrium condition like $V(k) = X^T(k)PX(k)$ giving an extraordinary restriction onto system performance, where the derivative of a candidate Lyapunov function is expressed as:

$$\Delta V(k) = V(k+1) - V(k) \tag{31}$$

Therefore,

$$V(k+1) = \begin{bmatrix} x_p(k+1) \\ \hat{x}_p(k+1) \\ z(k+1) \\ x_c(k+1) \end{bmatrix}^T P \begin{bmatrix} x_p(k+1) \\ \hat{x}_p(k+1) \\ z(k+1) \\ x_c(k+1) \end{bmatrix} \tag{32}$$

since the related Lyapunov function is proposed as:

$$V(x) = x(k)^T P x(k) \tag{33}$$

Now in terms of the augmented states is expressed as

$$V(k) = \sum_{i=1}^{m} \begin{pmatrix} x_{pi}(k+1) \\ \hat{x}_{pi}(k+1) \\ z_i(k+1) \\ x_{ci}(k+1) \end{pmatrix}^T P \begin{pmatrix} x_{pi}(k+1) \\ \hat{x}_{pi}(k+1) \\ z_i(k+1) \\ x_{ci}(k+1) \end{pmatrix} \tag{34}$$

The complete augmented states in terms of the fuzzy rules are given as

$$V(k) = \sum_{j=1}^{m}\sum_{i=1}^{m} \begin{pmatrix} h_jA_j^p \begin{bmatrix} x_p(k) \\ \hat{x}_p(k) \end{bmatrix} + h_jh_i\rho_j^pB_j^p(c_c^ix_c(k-t_{cai})) \\ z(k) + H_j^pz(k) \\ f_j^pz(k) + k_j^pc_j^p \begin{bmatrix} x_p(k) \\ \hat{x}_p(k) \end{bmatrix} + k_j^pT_j^pB_j^ph_ic_c^ix_c(k-t_{cai}) \\ h_iA_i^cx_c(k) + \rho_i^cB_i^ch_ic_p^j \begin{bmatrix} x_p(k-t_{scj}) \\ \hat{x}_p(k-t_{scj}) \end{bmatrix} \end{pmatrix}^T P \begin{pmatrix} h_jA_j^p \begin{bmatrix} x_p(k) \\ \hat{x}_p(k) \end{bmatrix} + h_jh_i\rho_j^pB_j^p(c_c^ix_c(k-t_{cai})) \\ z(k) + H_j^pz(k) \\ f_j^pz(k) + k_j^pc_j^p \begin{bmatrix} x_p(k) \\ \hat{x}_p(k) \end{bmatrix} + k_j^pT_j^pB_j^ph_ic_c^ix_c(k-t_{cai}) \\ h_iA_i^cx_c(k) + \rho_i^cB_i^ch_ic_p^j \begin{bmatrix} x_p(k-t_{scj}) \\ \hat{x}_p(k-t_{scj}) \end{bmatrix} \end{pmatrix} \tag{35}$$

Considering current local observer for each fuzzy rule

$$k_j^p = k_{1j} + k_{2j} \tag{36}$$
$$(H_jC_j^p - I)E_j = 0 \tag{37}$$
$$T_j^p = (I - H_jC_j^p) \tag{38}$$
$$f_j^p = A_j^p - H_j^pC_j^pA_j^p - k_{1j}C_j^p \tag{39}$$
$$k_{2j} = f_j^pH_j^p \tag{40}$$

Therefore, by maintaining local structure of augmented status it is possible to provide stability as global condition even in the case of TKS inter-relation for local models. In this case Equation (35) can be expressed as

$$\begin{bmatrix} N_j^p & h_jh_iM_j^i & 0 & 0 & 0 \\ T_j & \Delta_j^i & \Theta_j^c & 0 & 0 \\ 0 & 0 & \Omega_j & 0 & 0 \\ 0 & 0 & 0 & \Psi_i^c & h_jh_i\Gamma_j^i \end{bmatrix} \begin{bmatrix} x_p^c \\ x_{c1} \\ Z \\ x_c \\ x_{p1}^c \end{bmatrix} \tag{41}$$

$$K_j^i = \begin{bmatrix} N_j^p & h_jh_iM_j^i & 0 & 0 & 0 \\ T_j & \Delta_j^i & \Theta_j^c & 0 & 0 \\ 0 & 0 & \Omega_j & 0 & 0 \\ 0 & 0 & 0 & \Psi_i^c & h_jh_i\Gamma_j^i \end{bmatrix} \tag{42}$$

where the given expression is

$$N_j^p = h_jA_j^p \tag{43}$$
$$h_jh_iM_j^i = h_jh_i\rho_j^pB_j^pc_i \quad \therefore M_j^i = \rho_j^pB_j^pc_i \tag{44}$$
$$\Omega_j = (1 + H_j^p) \tag{45}$$
$$T_j = k_j^pc_j^p \tag{46}$$
$$\Delta_j^i = t_j^pB_j^ph_ic_j^i \tag{47}$$
$$h_jh_i\Lambda_j^i = \rho_ih_iB_i^ch_jc_j^p \tag{48}$$
$$\Theta_i^c = h_iA_i^c \tag{49}$$

where

$$x_{p1}^c = \begin{bmatrix} x_p(k-\tau_{scj}) \\ \hat{x}_p(k-\tau_{scj}) \end{bmatrix} \tag{50}$$
$$x_{c1} = x(k-\tau_{cat}) \tag{51}$$
$$x_p^c = \begin{bmatrix} x_p(k) \\ \hat{x}_p(k) \end{bmatrix} \tag{52}$$
$$K_j^iPK_j^{i^T} = V(k+1) \tag{53}$$

The related k is given as

$$K_j^i \begin{bmatrix} x_p^c \\ x_{c1} \\ Z \\ x_c \\ x_{p1}^x \end{bmatrix} PK_j^{iT} \begin{bmatrix} x_p^c \\ x_{c1} \\ Z \\ x_c \\ x_{p1}^c \end{bmatrix} - \begin{bmatrix} x_p^c \\ x_{c1} \\ Z \\ x_c \\ x_{p1}^c \end{bmatrix} P \begin{bmatrix} x_p^c \\ x_{c1} \\ Z \\ x_c \\ x_{p1}^c \end{bmatrix} < 0 \tag{54}$$

Therefore,

$$X_\rho = \begin{bmatrix} x_p^c \\ x_{c1} \\ Z \\ x_c \\ x_{p1}^c \end{bmatrix} \tag{55}$$

$$\sum\nolimits_{j=1}^{N} \sum\nolimits_{i=1}^{N} \left\{ K_j^i X_\rho P (K_j^i)^T X_\rho^T - X_\rho P X_\rho^T \right\} < 0 \tag{56}$$

Hence

$$\sum\nolimits_{i=1}^{N} \sum\nolimits_{j=1}^{N} \sum\nolimits_{k=1}^{N} \sum\nolimits_{l=1}^{n} \left[h_i h_j h_k h_l X_\rho^T \left[K_j^i P K_j^{iT} - P \right] X_\rho \right] = 0 \tag{57}$$

$$\frac{1}{4} \sum\nolimits_{i=1}^{N} \sum\nolimits_{j=1}^{N} h_i h_j X_\rho^T \left[K_j^i P K_j^{iT} - 4P \right] X_\rho < 0 \tag{58}$$

Further, solving this condition is numerically possible thorough LMI solving strategy, but current system representation ending being quite restrictive although possible by using Fuzzy Takagi Sugeno.

5. **Case Study.** The case study needs to enhance the capability to communicate multiple nodes connected through a single network among similar communication levels. A requirement of case study is the multiple variable strategies in terms of local time delays in order to determine variable structure proposing state enhancement during local conditions. Furthermore case study needs to reveal how an integrating strategy using Fuzzy TKS control considering local conditions may overcome bounded time delays as well as losing local states at the same scenario. Case study needs to be defined in terms of a computer network allowing local communications and online priority exchange; therefore, a holistic approach of such condition is indeed necessary to observe complex situations like described in previous section. Current experimental setup, Figure 5 is based upon 10 nodes transmitting in the following conditions using True-Time as simulation benchmark, consisting on:

10 Nodes, Ethernet type network with 100 mbps, 200 ms of maximum delays, system simulation True-Time

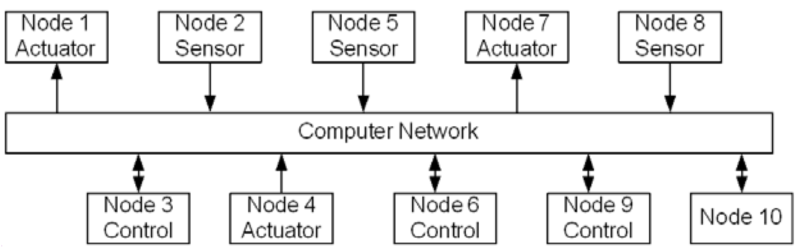

FIGURE 5. Networked control system

In terms of periodic and aperiodic tasks, the plant that uses network control systems is:

$$A_1 = \begin{bmatrix} -0.3 & 0 & 3 \\ -4 & -2 & 0.1 \\ 0.1 & 0.3 & -0.1 \end{bmatrix} \; A_2 = \begin{bmatrix} -0.3 & 0 & 2 \\ -2.2 & -0.2 & 0.01 \\ 1.1 & 0.3 & -0.2 \end{bmatrix} \; A_3 = \begin{bmatrix} -2.2 & 0 & 2 \\ 0.2 & -1.2 & 5.2 \\ 1 & -0.2 & 3.21 \end{bmatrix}$$

where the periodic tasks are expressed in terms of consumption and periods as shown in Table 3. The related aperiodic tasks are represented in Table 4.

TABLE 3. Periodic tasks integrated to current numeric case study

Task	Nodes	Consume	Period
Task 1	Node 1	1	10
Task 2	Node 2	2	16
Task 3	Node 3	1	15
Task 4	Node 4	1	20
Task 5	Node 5	1	15
Task 6	Node 6	2	21
Task 7	Node 7	1	9
Task 8	Node 8	1	17
Task 9	Node 9	1	15
Task 10	Node 10	2	21

TABLE 4. Aperiodic tasks integrated to current numeric case study

Task	Consume	Deadline
T_{a1}	0.3	11
T_{a2}	0.9	16
T_{a3}	0.7	13

Therefore, common situations of bounded time delays are described as follows. Local time delays appear as part of priority exchange ordering as noted in Equation (2). Following Table 3 and Table 4, the fuzzy rules are created by using this representation and combined Equations (6) and (7). This experimental setup (simulation) is preliminary to a real implementation since switching conditions are enhanced as neglected time delays.

If a local fault appears, the system modifies its structure according to Equation (20). However, stability still can be reached, since faults are strictly local and unitary in terms of similar fault presence, and bounded on time. This assumption is quite restricted on real life, albeit possible for incipient faults and bounded time delays. Therefore, how to cope in degradable systems due to intermittent faults is out of the scope of this paper. Faulty conditions, as well as inherent structure characteristics, are as well out of the scope of this paper. The focus of current approximation is to establish fault effects into system structure considering time deadlines. Following this restricted condition, it is possible to establish stability requirements following one sensor missing and the corresponding local time delay, since Equation (16) is not affected by the structure of the system but current observer is defined in terms of local situation albeit fault presence and local variable structure. Now, the structure of ρ_j^* is a matrix $(N \times N)$ which is coherent on the dimensions of B_j^* as expressed as:

$$\rho_i^* = \left[\left[\begin{array}{ccc} 1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 1 \end{array} \right] \right] \tag{59}$$

As soon as a local fault appears, ρ_j^* matrix is modified. The local fault is replaced by a cero condition as shown in Equation (60), and current local observer produces the related estimated state with local fault covered.

$$\rho_i^* = \left[\left[\begin{array}{ccc} 0 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 1 \end{array} \right] \right] \tag{60}$$

In this case, linear control gains are obtained using Equations (41) and (42) where global stability is provided since continuing scheme is valid. Following this strategy current results show the convenience of this approach since local time delays are bounded accordingly.

$$K_1 = [0.2\ 0.1\ 0.3],\ K_2 = [0.3\ \ -0.5\ \ -1.3],\ K_3 = [0.4\ \ -0.6\ \ -0.3]$$

Figure 6 presents the response of the system in terms of these three scenarios (A_1 A_2 A_3) where three different plants considering the same number of control gains are considered. Now, in terms of local fault scenarios, system response is presented in Figure 7 where the faults are resolved by using aperiodic tasks presented in Table 4. The reader should remember that further study of the faults needs to be provided although this is out of the scope of this paper. These results are preliminary in terms of the simulation setup.

6. **Conclusions.** In an NCS, time delays can be modeled using real-time dynamic scheduling algorithms; however, the resulting delays are time varying and stationary; therefore, related local control laws need to be designed according to this characteristic. Time integration is the key global issue to be taken into consideration as well as local variable structure. Global stability is reached by the use of Takagi-Sugeno fuzzy control design,

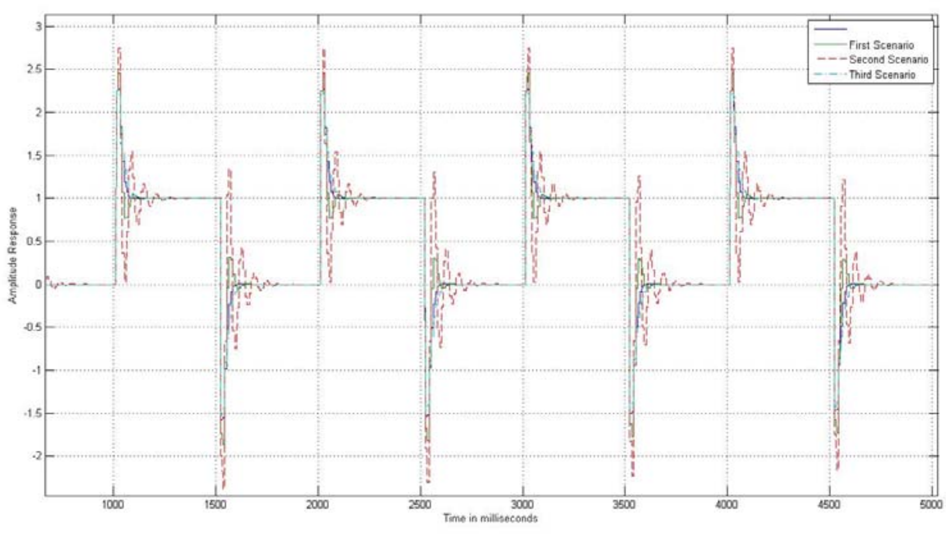

FIGURE 6. System responses in terms of the three scenarios within fault free conditions

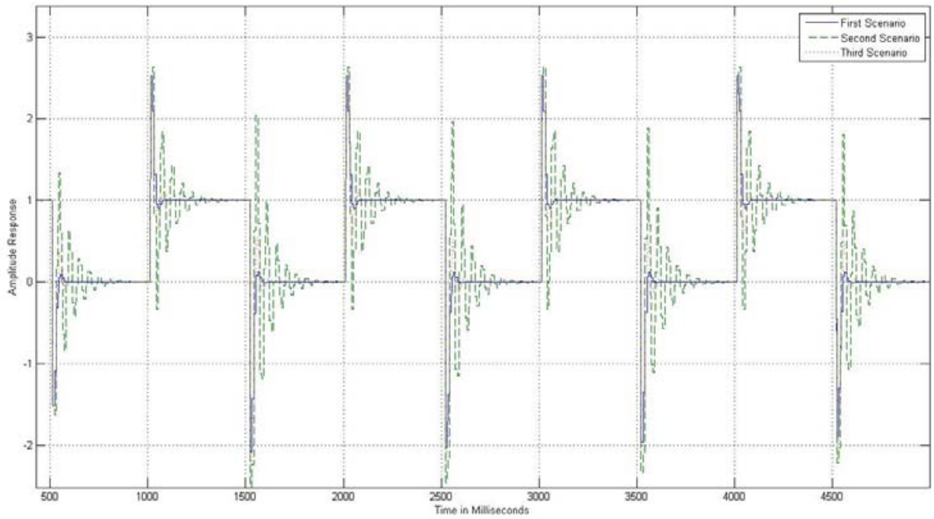

Figure 7. System response in terms of fault scenarios

where a nonlinear combination is followed by a current sequence of states, which are partially delayed due to the communication behavior. Since, this powerful technique such as Fuzzy TKS is possible to guarantee but features time delay response as well as local variable structure.

Fault conditions are overcome through two strategies: 1) by scheduling approximation and 2) by control design, considering inherent time delays. In this case, this approach takes the solely effect of faults as a result of certain local malfunction, which is bounded to this. Fault nature, as well as fault treatment, is out of the scope of this paper, since it is necessary to establish a reliability study. Fault status is considered to be only local and bounded, where the unique effect is the absence of current measure lack of local and current state, as well as inherent time delays. The first condition is preserved by the use of ρ_j^*, and local time delays appear to be feasible by the use dynamic scheduling, since these are already known as part of time manipulation onto tasks belonging to studied system. Priority exchange allows system to be known in terms of local time delays.

The use of a dynamic scheduling approach allows the system to be predictable and bounded, and therefore, time delays can be modeled in these terms. Moreover, the resulting dynamic representation tackles the inherent switching per scenario. However, this approach has the main drawback that context switch may be invoked every time that an aperiodic task takes place, and it is possible to be executed. In this case, inherent time delays to this action are taken into account to be processed as uncertainties. Thus, in this paper, time delays and the appearance of local faults are taken to develop a fuzzy model of the controller, capable of solving this nonlinear behavior. This control approach is feasible, since local faults are known as well as bounded time delays.

Moreover, variable structure allows faults to be bounded as long as current observer may tackle lack of one state. Moreover, stability needs to be guaranteed in these terms.

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