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A Fuzzy Networked Control System Following Frequency Transmission Strategy

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Abstract: At present, network control systems employ a common approximation to solve the connectivity issue due to time delays coupled with external factors . However, this approach tends to be complex in terms of time delays, and the inherent local phase is missing. Therefore, it is necessary to study the behavior of the delays as well as the integration of the differential equations of these bounded delays. The related time delays need to be known a priori, but from a dynamic real-time perspective in order to understand the dynamic phase behavior. The objective of this paper is to demonstrate the inclusion of the data frequency transmission and time delays that are bounded as parameters of the dynamic response from a real-time scheduling approximation, considering the local phase situation. The related control law is designed considering a fuzzy logic approximation for nonlinear time delays coupling. The main advantage is the integration of this behavior through extended state space representation. This keeps certain linear and bounded behavior leading to a stable situation during an events presentation, based on an accurate data transmission rate. An expected result is that the basics of the local phase missing as a result of the local bounded time delays from the lack of tide synchronization conforms to the modeling approximation.
Keywords: Fuzzy networks control (FNC), frequency control, local phase challenge.

1 Introduction

Real-time restrictions are the primary cause of time delays when general conditions tend to be periodic and repeatable . The control design and stability analysis of network-based control systems (NCSs) have been studied in recent years, and approaches such as the codesign strategy have been developed [2]. The main advantages of these types of systems are their low cost, small wiring volume, distributed processing, simple installation, ease of maintenance, and reliability.

A key issue in an NCS is the effect of network-induced delay on the system performance. The delay can be constant, time-varying, or even random depending on the scheduler, network type, architecture, or operating systems. [16] analyzed several important facets of NCSs and introduced models for their delays, including first a fixed delay, then an independently random delay, and finally a Markov process. This work introduced optimal stochastic control theorems for NCSs based upon independently random and Markovian delay models. [20], introduced static and dynamic scheduling policies for the transmission of sensor data over a continuous time linear time-invariant (LTI) system. They introduced the notion of the maximum allowable transfer interval (MATI), which is the longest time after which a sensor should transmit a data. The MATI determines that the Lyapunov function of the system under consideration is strictly decreasing at all times. [22], extended the work of Walsh et al. by developing a theorem that ensures the decrease of a Lyapunov function for a discrete-time LTI system at each sampling instant, using two different bounds. This used a number of different linear matrix inequality (LMI) tools for analyzing and designing optimally switched NCSs. The MATI is an important concept for bounded time delays and the maximum local dephasing problem.

Alternatively, [23] considered both the network induced delay and the time delay in a plant, and proposed a controller design method using the delay-dependent approach. An appropriate Lyapunov functional candidate was used to obtain a memoryless feedback controller that was derived by solving a set of LMIs. [21] modeled 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 was presented to model the NCSs. Based on this model, the $H\infty$ state feedback controller was constructed via a set of LMIs. [7] introduced a model transformation for the delay-dependent stability of systems with time-varying delays in terms of LMIs. Their model also refined results from delay-dependent $H\infty$ control and extended them to the case of time-varying delays. Based upon this review, the present paper defines a model that integrates time delays into a fuzzy control for NCSs [18, 22] taking into consideration the local phase margin induced by the computer network as a result of online reconfiguration.

Since NCS is modified according to time delays, reconfiguration is a transition that modifies the structure of a system so it changes its representation of states. The objective of this paper is to show how the control of frequency transmission has a bounded impact over a network control system.

In general there are two types of tasks in a NCS. The first is a periodic task that is time-triggered. In this type, tasks have a transmission time c_i, a constant period of execution p_i, and a deadline d_i. Thus, the sum of the transmission times of n nodes' tasks, divided into their periods p_i for a fixed priority scheduler [15].

The network scheduler is a high priority in the design of a distributed system and it is also critical in an NCS, since if there is no scheduling between nodes, data transmissions may occur simultaneously which lead to collisions or bandwidth violations. This behavior results in a transmission with time delays, leading to failure in complying with deadlines, data loss, and an obvious decrease in system performance due to local phase misleading. A good scheduling control algorithm minimizes the decrease in system performance [4]; nevertheless, there are no global schedulers that guarantee optimal system performance [15]. Some strategies include methods in which nodes generate proper control actions in order to optimally utilize bandwidth [11, 12]. In the digital control case, the performance only depends on the sampling frequency without uncertainties. For networked control, the minimum transmission frequency f_m is necessary to guarantee suitable system performance. As the transmission frequency increases the system performance improves; however, the load on the network also increases until a maximum transmission frequency f_M is reached, then the system performance decreases because the network is overloaded. It is very important to modify the transmission frequency to obtain better system performance within a bounded region that is particularly defined for the current system needs.

In control systems, several modeling strategies for managing time delay within control laws have been studied by different research groups. [16] proposed the use of a time delay scheme integrated to a reconfigurable control strategy, based on a stochastic methodology. [9] described how time delays are used as uncertainties, which modify pole placement of a robust control law. [8] presented an interesting case of fault tolerant control approach related to time delay coupling. [3] studied reconfigurable control from the point of view of structural modification, establishing a logical relation between dynamic variables and the respective faults. Finally, [19] and [2] considered that reconfigurable control strategies perform a combined modification of system structure and dynamic response; thus, this approach has the advantage of bounded modifications over system response.

The present paper proposes a mixed strategy using bounded variable time delays and frequency transmission as the data communication rate. The novelty of this approximation is that it guarantees schedulability as well as stability in the presence of bounded time delays, considering an accurate data transmission rate through the network. This is feasible since the time delays are bounded according to scheduler response.

2 Frequency control

As presented in [17], a fuzzy approach to network control systems allows a real representation of bounded time delays and control design. Specifically, this can be used when time delays are the result of the controlling frequency transmission, as presented previously. Several potential scenarios are presented that follow this time delay behavior. In fact, the number of scenarios is finite since the combinatorial formation is bounded. Therefore, any strategy for designing a control law needs to take into account the gain scheduling approximation.

Therefore, an alternative strategy is the use of control for periodic messages, namely the control of frequency transmissions as presented by [6]. The change in frequency transmission of each node through time is represented using the relations of frequencies for a particular node and among all nodes. This means that the frequency transmission rate of each node is influenced by changes in the transmission rate of the other nodes.

Upper and lower bounding are necessary since the data transmission frequency of the network can be high. Due to uncertainties during sensing, the system may become unstable; similarly, the low data frequency transmission may result in undersampling which goes to control performance weakness. Having defined this dynamic bounding strategy, it becomes interesting to examine the effects of known time delays over a well-defined network control approximation.

3 Modified Frequency Transmission for NCS's

The following section presents an illustrative experiment considering a twin rotor case study as well as a magnetic levitation system (Fig. 1, 2) These cases include the local dynamics necessary for a complete networked control system where a global computer network is implemented.

3.1 Twin Rotor and Magnetic Levitation System Equations

The free-body diagram of the twin Rotor is illustrated in Figure 1 and from this the next nonlinear equations of motion are obtained using the Euler-Lagrange formula [24]:

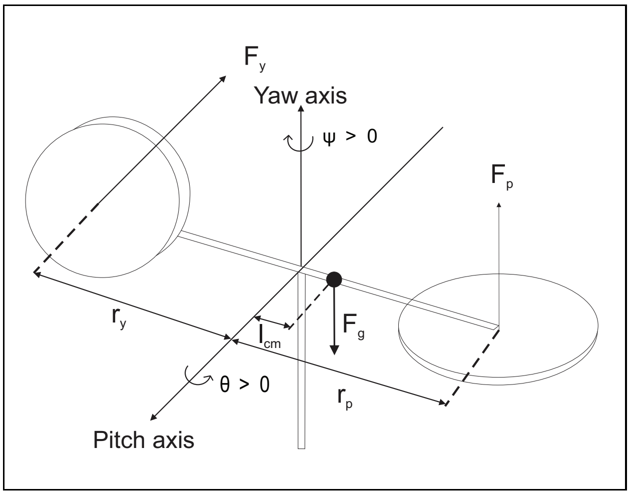

Figure 1: Twin Rotor.

$$
\begin{aligned}
\ddot{\theta} &= \frac{1}{(J_{eqp} + m_{heli} l_{cm}^2)} (K_{pp} V_{mp} + K_{py} V_{my} - \\
& m_{heli} l_{cm}^2 (sin(\theta) cos(\theta)) \dot{\psi}^2 - cos(\theta) m_{heli} g l_{cm} - B_{qp} \dot{\theta}) \\
\ddot{\psi} &= \frac{1}{(J_{eqy} + m_{heli} l_{cm}^2 cos(\theta)^2)} (K_{yp} V_{mp} + K_{yy} V_{my} + \\
& 2 m_{heli} l_{cm}^2 cos(\theta) sin(\psi) \dot{\theta} \dot{\psi} - B_{qy} \dot{\psi})
\end{aligned} \tag{1}
$$

where:
J_{eqp} Total moment of inertia about pitch axis
J_{eqy} Total moment of inertia abut yaw axis
K_{pp} Thrust force constant acting on pitch axis from pitch motor/propeller
K_{yy} Thrust force constant acting on yaw axis from yaw motor/propeller
K_{py} Thrust force constant acting on pitch axis from yaw motor/propeller
K_{yp} Thrust force constant acting on yaw axis from pitch motor/propeller
B_{qp} Equivalent viscous damping about pitch axis
B_{qy} Equivalent viscous damping about yaw axis
l_{cm} Center of mass length along helicopter body from pitch axis
m_{heli} Total moving mass of helicopter
g Gravitational constant

Table 1 shows the values of this parameters.

In the case of magnetic levitation system model [25] specifications are derived from the mechanical and electric system representation as illustrated in Figure 2.

The nonlinear equations for the Magnetic Levitation System are:

$$
\begin{aligned}
\dot{x_1} &= x_2 \\
\dot{x_2} &= \frac{-K_m x_3^2}{2 M_b (x_1)^2} + g \\
\dot{x_3} &= \frac{1}{L_c} (-R x_3 + u)
\end{aligned}
$$

where $R = R_c + R_s$ and $u = V_c$ input voltage and

Table 1: System Specifications

Symbol	Value	Unit
J_{eqp}	0.0348	$kg \cdot m^2$
J_{eqy}	0.0432	$kg \cdot m^2$
K_{pp}	0.204	$N \cdot m/V$
K_{yy}	0.072	$N \cdot m/V$
K_{py}	0.0068	$N \cdot m/V$
K_{yp}	0.0219	$N \cdot m/V$
B_{qp}	0.800	N/V
B_{qy}	0.318	N/V
m_{heli}	1.3872	kg
l_{heli}	0.186	m

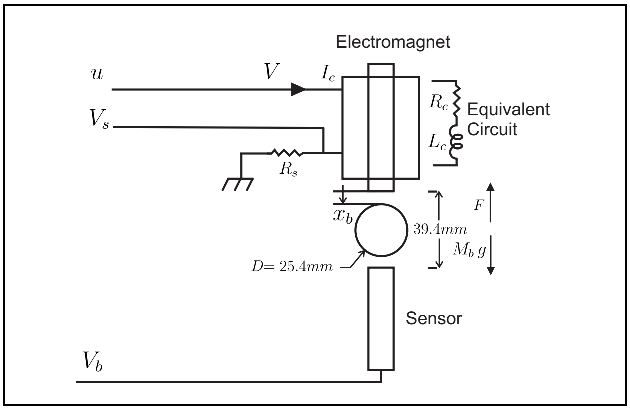

Figure 2: Magnetic Levitation System

Table 2: System parameters

Symbol	Value	Unit
L_c	0.4125	H
R_c	10	Ω
R_s	1	Ω
k_m	$6.5308e^{-5}$	Nm^2/Amp^2
M_b	0.068	kg
g	9.81	m/s^2

R_c electromagnet resistance
R_s resistor in series wiht the coil
K_m constant of electromagnet force
M_b mass of the ball
g gravitacional constant
L_c coil inductance

The values of the parameters are provided in Table 2

These systems are distributed and communicated through an Ethernet network to implement a complete networked control system, as depicted in Figure 3.

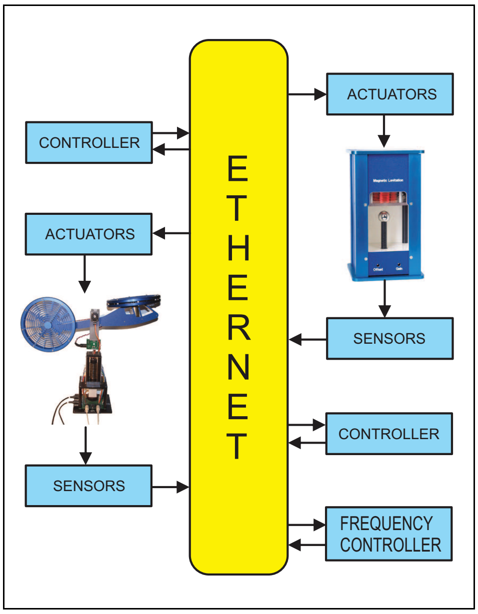

Figure 3: NCSs

In this work, we define three rules of fuzzy model to approximate the twin rotor nonlinear system, as follows:

Rule 1:

IF x_1 is about $0°$,

THEN $\dot{x} = A_1 x + B_1$

Rule 2:

IF x_1 is about $40°$,

THEN $\dot{x} = A_2 x + B_2$

Rule 3:

IF x_1 is about $-40°$,

THEN $\dot{x} = A_3 x + B_3$

where x_1 is the pitch angle and

$$A_1 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -9.2593 & 0 \\ 0 & 0 & 0 & -3.4868 \end{bmatrix}$$

$$B_1 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 2.3611 & 0.0787 \\ 0.2401 & 0.7895 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 18.8362 & 0 & -9.2768 & 0 \\ 2.5148 & 0 & 0 & -4.4618 \end{bmatrix}$$

$$B_2 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 2.3667 & 0.0789 \\ 0.3073 & 1.0102 \end{bmatrix}$$

$$A_3 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -18.8362 & 0 & -9.2768 & 0 \\ -2.5148 & 0 & 0 & -4.4618 \end{bmatrix}$$

$$B_3 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 2.3667 & 0.0789 \\ 0.3073 & 1.0102 \end{bmatrix}$$

Figure 4 shows the membership function for the rules of the helicopter fuzzy model.

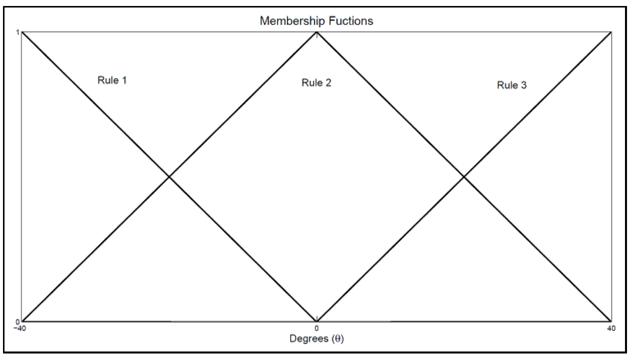

Figure 4: Membership Functions of Helicopter Model

Here, two fuzzy rules are defined to approximate the magnetic levitation system by means of two linear models, as follows:

Rule 1:

IF x_1 is about $0.006\,m$,

THEN $\dot{x} = A_1 x + B_1$

Rule 2:

IF x_1 is about $0.014\,m$,

THEN $\dot{x} = A_2 x + B_2$

where x_1 is the ball position in meters and

$$A_1 = \begin{bmatrix} 0 & 1 & 0 \\ 4097.8 & 0 & -25.6 \\ 0 & 0 & -26.7 \end{bmatrix}$$
$$A_2 = \begin{bmatrix} 0 & 1 & 0 \\ 1509.2 & 0 & -14.2 \\ 0 & 0 & -26.7 \end{bmatrix}$$
$$B_1 = B_2 = \begin{bmatrix} 0 \\ 0 \\ 2.4242 \end{bmatrix}$$

The membership functions for this case are shown in Figure 5

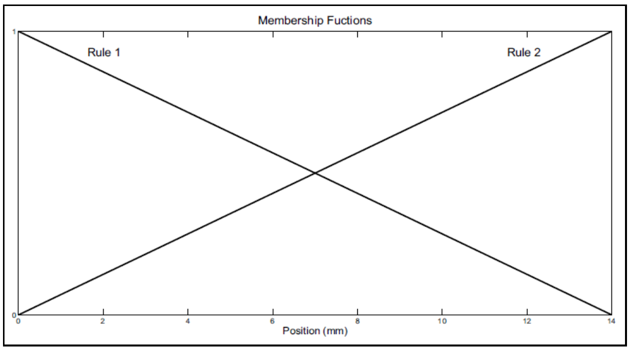

Figure 5: Membership Functions of Levitator Model

The fuzzy controller for each system is design by PDC as follows:

Control Rule i:
IF $z_i(t)$ is M_{i1} and $z_n(t)$ is M_{in}
THEN $u = -K_i x$

The feedback gain matrix K_i was obtained by means of the linear-quadratic regulator (LQR) of each linear system. The stability analysis of the fuzzy control system should be performed employing a numerical mathematical program, for example, using Matlab's linear matrix inequalities toolbox to check feasibility.

$$K_1 = \begin{bmatrix} 18.9369 & 1.9770 & 7.4917 & 1.5258 & 7.0292 & 0.7685 \\ -2.2192 & 19.4463 & -0.4496 & 11.8949 & -0.7685 & 7.0292 \end{bmatrix}$$

$$K_2 = \begin{bmatrix} 28.5899 & 2.0444 & 7.8331 & 1.6059 & 7.0264 & 0.7933 \\ -2.3969 & 19.3161 & -0.5528 & 11.5476 & -0.7933 & 7.0264 \end{bmatrix}$$

$$K_3 = \begin{bmatrix} 51.0473 & 6.1419 & 28.4307 & 4.7239 & 22.2386 & 2.3333 \\ -6.3519 & 59.4161 & -2.4313 & 41.5536 & -2.3333 & 22.2386 \end{bmatrix}$$

Following the same procedure for the fuzzy helicopter controller to find the matrix gains, we obtain the following matrix:

$$K_1 = \begin{bmatrix} -11971 & -187 & 53 & 7 \end{bmatrix}$$
$$K_2 = \begin{bmatrix} -5739 & -147.7 & 32.1 & 10 \end{bmatrix}$$

Now, in terms of frequency transitions, the dynamics representation is given as follows:

$$\dot{x} = \begin{bmatrix} 0.1250 & 0.1300 & 0.1350 & 0.1400 & 0 \\ 0.1060 & 0.1111 & 0.1160 & 0.1210 & 0 \\ 0.0900 & 0.0950 & 0.1000 & 0.1050 & 0 \\ 0.0135 & 0.0185 & 0.0235 & 0.0286 & 0 \\ 0.001 & 0.001 & 0.001 & 0.001 & 1 \end{bmatrix} x + \begin{bmatrix} 40 & 0 & 0 & 0 & 0 \\ 0 & 45 & 0 & 0 & 0 \\ 0 & 0 & 50 & 0 & 0 \\ 0 & 0 & 0 & 175 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} u$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} x$$

Where
$x_1 =$ is the frequency transmission in node 1
$x_2 =$ is the frequency transmission in node 2
$\vdots$
$x_n =$ is the frequency transmission in node n
$x_c =$ is the network utilization

and

$u_1 =$ is the frequency input 1 of system
$u_2 =$ is the frequency input 2 of system
$\vdots$
$u_n =$ is the frequency input n of system
$u_c =$ is the frequency input c of system

We design a control for the trajectory tracking, which is the desired frequency transmission by means of the LQR algorithm, so that the gain matrix obtained is:

$$K = \begin{bmatrix} 3.5521 & 0.0027 & 0.0023 & 0.0007 & 0.0003 \\ 0.0030 & 3.5101 & 0.0021 & 0.0006 & 0.0003 \\ 0.0029 & 0.0024 & 3.4763 & 0.0005 & 0.0003 \\ 0.0029 & 0.0022 & 0.0017 & 3.2792 & 0.0002 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 5.7417 \end{bmatrix}$$

and the integral gain matrix is

$$K_I = \begin{bmatrix} -48.3570 & 0.0085 & 0.0150 & 0.0518 \\ -0.0085 & -48.3184 & 0.0064 & 0.0389 \\ -0.0150 & -0.0064 & -48.2873 & 0.0297 \\ -0.0398 & -0.0299 & -0.0228 & -62.5185 \\ 0.0048 & 0.0048 & 0.0048 & 0.0050 \end{bmatrix}$$

The nominal values and schedulability regions were found using Truetime [5] and are shown in Table 3. These take into account that the frequency system models 5 network nodes; but in the experiment, only 4 nodes are employed because the last node corresponds to the use of the network.

For the Stability proof it is necessary to take into account there are two transmission bound, superior and lower bound and consider the schedulability restriction.

The schedulability restriction is given taking the maximum frequency value if keeps the restriction.

In the other hand for the lower transmission value it is necessary to prove that this values are the maximum allowable delay bound which guaranty stability of the NCS. In [10] it is presented a LMI formulation to find the maximum allowable delay bound.

If there exist $P > 0$, $Q_i > 0$, X_i, Y_i and Z_i, $i = 1, ..., N$, such that

$$\begin{bmatrix} \mathfrak{P}_{11} & \mathfrak{F}^T \mathfrak{L} \\ \mathfrak{L}\mathfrak{A} & -\Gamma \end{bmatrix} < 0, \begin{bmatrix} X_i & Y_i \\ Y_i^T & Z_i \end{bmatrix} \geqslant 0$$

where

$$\mathfrak{P}_{11} = \begin{bmatrix} \mathfrak{F}_{11} & P\mathfrak{F}_1 - \mathfrak{Y} \\ \mathfrak{F}_1^T P - \mathfrak{Y} & -\mathfrak{D} \end{bmatrix},$$

$$\mathfrak{F} = \begin{bmatrix} F & F_1 & ... & F_N \end{bmatrix},$$

$$\mathfrak{F}_1 = \begin{bmatrix} F_1 & ... & F_N \end{bmatrix},$$

$$\mathfrak{Y} = \begin{bmatrix} Y_1 & ... & Y_N \end{bmatrix},$$

$$\mathfrak{L} = \tau \begin{bmatrix} Z_1 & ... & Z_N \end{bmatrix},$$

Table 3: Nominal frequency, maximum, minimum and transmission time

Node	$c_i\,(s)$	$f^i_{nom}\,(Hz)$	$0.9\ f^i_{min}\,(Hz)$	$f^i_{max}\,(Hz)$
1	0.001	280	40	83
2	0.001	300	45	98
3	0.001	310	50	70
4	0.001	450	175	212
5	0.001	480	165	196
6	0.001	500	160	188

$$\mathfrak{D} = diag\left\{Q_1, ..., Q_N\right\},$$

$$\Gamma = \bar{\tau} diag\left\{Z_1, ..., Z_N\right\},$$

$$\mathfrak{F}_{11} = F^T P + PF + \sum_{i=1}^{N} \left\{Y_i + Y_i^T + \bar{\tau} X_i + Q_i\right\}$$

the system is asymptotically stable for any time-delay τ_i satisfying $0 \leqslant \tau_i \leqslant \bar{\tau}_i$, $i = 1, ..., N$ Solving LMIs with MATLAB TOOLBOX for each subsystem of the Fuzzy representation the next τ_i are found

$\tau_1 = 0.0058$, $\tau_2 = 0.0071$, and $\tau_3 = 0.0067$

Which in frequency terms are 172.42, 140.85 and 149.25 Hz respectively being consistent with the values previously found.

Now in the twin rotor case the values are:
$\tau_1 = 0.050$, $\tau_2 = 0.067$, and $\tau_3 = 0.050$

In frequency terms are 20, 15 and 20 Hz respectively which approach to the values previously found in Table 3.

4 Frequency Control Design

To implement this experiment, 7 nodes employed to obtain a complete distributed NCS configuration as follows: 3 nodes to the twin rotor system (sensor, actuator, and controller), 3 to the magnetic levitation system (sensor, actuator, and controller), and 1 more used for perform frequency control. The latter node assigns the changes in the transmission frequency to sensors and controller nodes of the systems.

The platform was built with 10 Mbps Ethernet as communication medium and Quarc adquisition boards to accomplish data exchange between nodes. Quarc Matlab's toolbox provides an useful and straightforward way to stablish communication among several nodes which contain embedded Simulink models (in this case Twin Rotor and Levitation distributed models) by means its communication blocks.

The processes run at nominal frequency transmission values according to Table 3. The controller frequency node, which contains the embedded Simulink frequency model, modifies nominal to schedulability values by means LQR controller action, as seen in Figure 6. In this figure, the red and blue signals represent the helicopter's sensor and controller transmission frequency, respectively, and the green and brown signals depict the levitator's sensor and controller transmission frequency.

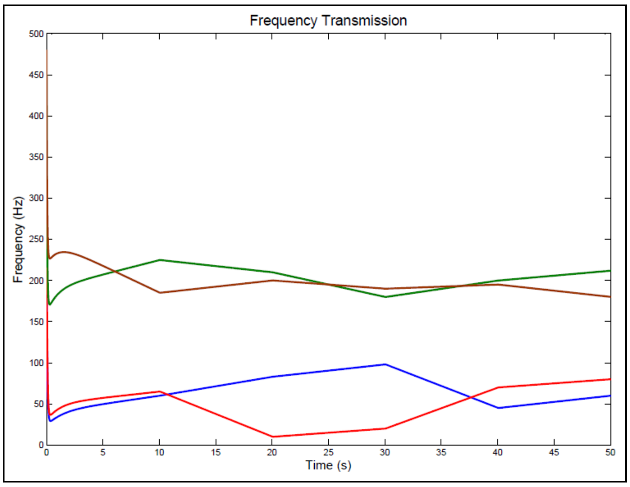

Figure 6: Frequency Transmission Transition

The results of these experiments are presented in Fig. 7 , in which the twin rotor presents a suitable response even with frequency transitions. The red color signal is the desired pitch and yaw angle, and the blue color signal is the obtained response.

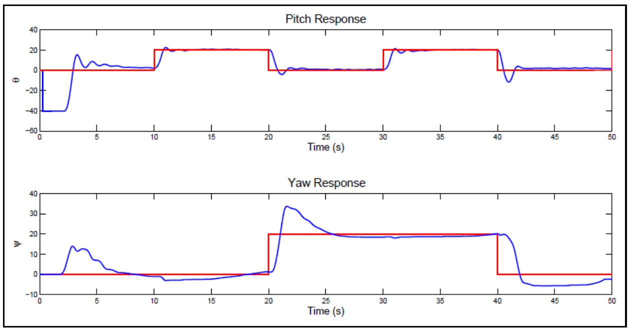

Figure 7: Pitch and Yaw angle when frequencies are whitin the bounds

In the second experiment, the transmission frequencies are outside the lower bound of the schedulability region for short time instants. It can be seen at $t = 10$ and $t = 30$ in Figure 8 where the frequencies leave the schedulability region for $5\,s$ and then return within the region.

The magnetic levitation system response, in terms of the current value and ball position during the frequency transmission change, is presented in Fig. 9. In this figure, the red color signal is the desired current and ball position, and the blue color signal is the system response.

The next result is obtained (Figure 10) when the frequencies change at $t = 25$ and $t = 40$ leaving slightly the schedulability region for $3\,s$ and $5\,s$ respectively and then the frequencies return within the region.

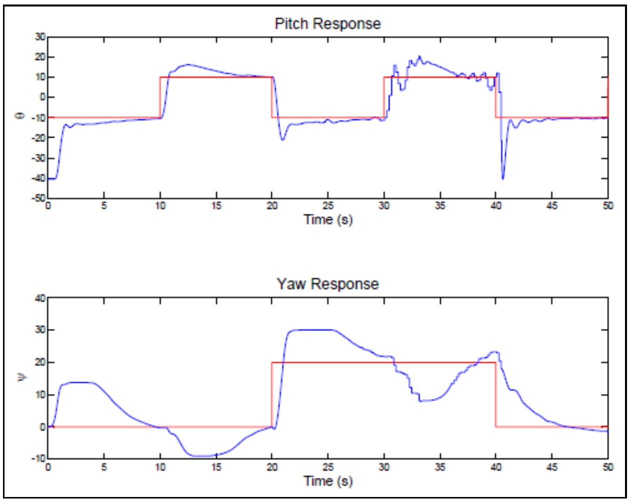

Figure 8: Pitch and Yaw angle when frequencies by instants are not within the bounds

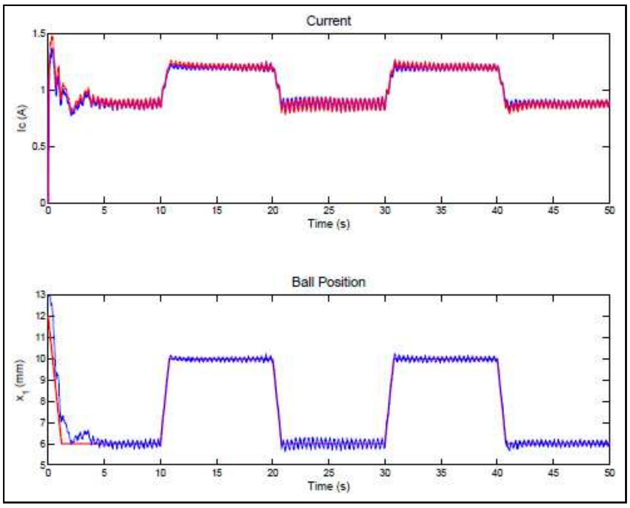

Figure 9: Current and ball position when frequencies are within the bounds

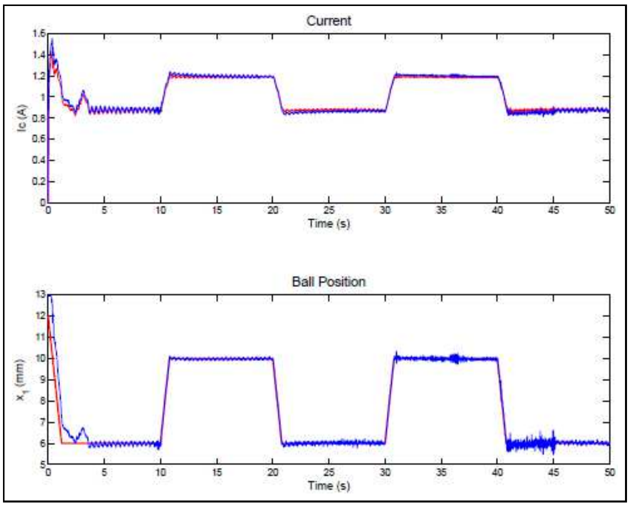

Figure 10: Current and ball position when frequencies by instants are not within the bounds

5 Conclusion

Currently, time delays can be modeled using a bounded frequency transmission control approach; however, the resulting delays are time varying and stationary. Therefore, a related local control law must be designed according to this characteristic, where time integration is the key global issue to be considered. Global stability is reached by the use of the Takagi Sugeno fuzzy control design, where nonlinear combination is followed by the current situation of the states. These are partially delayed due to the communication behavior in terms of the phasing problem. In this case, the bounded local stochastic variables are presented in terms of local phases.

The main contribution of this paper is the capability of determining the local time delays that can be aggregated per event, since the frequency transmission control contributes to the bound time response, resulting in a global problem of local synchronized elements. Therefore, fuzzy control may be attractive to guarantee global stability, since any condition is bound to be less than the sampling period of the worst-case scenario with no loss of generality. However, local phase missing is still an open problem, since these are stochastically calculated and linked to a tight synchronization situation.

The use of the dynamic scheduling approximation, as reviewed here, allows the system to be predictable and bounded; therefore, time delays can be modeled in these terms. Moreover, the resulting dynamic representation tackles the inherent switching situation per scenario. This approximation has the main drawback that the context switch may be invoked every time that a periodic 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 bounded known values and to modify the related local stochastic phase. Thus, there is desynchronizing global behavior of the network.

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