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Performance Evaluation of Diagnosis System According to Various Structures of Networked Control System

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Abstract: *Distributed control systems, often referred as "Networked control systems", are more and more used in many industrial applications. This paper investigates the influence of the networked control system structure on diagnosis system. The non deterministic network Switched Ethernet was considered in this study for its current use in several real-time systems. .*
Several scenarios were studied to analyse the performances of diagnosis system according to various structures of networked control system and network parameter packet losses. The Truetime simulator was used in this work to model the considered network.

Keywords: *Networked Control Systems (NCS), Switched Ethernet, NCS Structures, Truetime simulation, Residuals, Diagnosis and Packet losses.*

1. INTRODUCTION

Networked Control Systems (NCS) represent a complex research field due to their pluridisciplinary aspect. Thus, NCS studies have to take into account knowledges on network, computer and control, simultaneously.
The NCS are, in fact, systems where actuators, sensors, controllers and diagnosis system communicate over a network, figure1. They are more and more used in many fields such as mobile sensor networks, aircraft systems and industrial applications as in Flexible Manufacturing Systems (FMS), and Reconfigurable Manufacturing Systems (RMS).
Embedding network communication in the feedback control loop enables to improve the efficiency, the flexibility, the dependability and the modularity of the systems. Hence, this offers many advantages such as easy installation and reconfiguration, reduced weight, high reliability, and low setup and maintenance costs.
However, such strategy has many disadvantages. Unfortunately, the network implementation in the control systems makes NCS analysis and design complex. Thus, conventional control theories with ideal assumptions, such as synchronised control and non delayed sensing and actuation, must be re-evaluated before they can be applied to the NCSs. Indeed, the network induced delay makes the traditional study

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of time delay systems different. One of the most common problems caused by the network are packet losses due to communication noise, interference, or congestion and the frames scheduling which should be accommodated during the control system design. These artefacts can degrade the performance of control and diagnosis systems and can even destabilize the system [1], [2], [3], [4], [5].

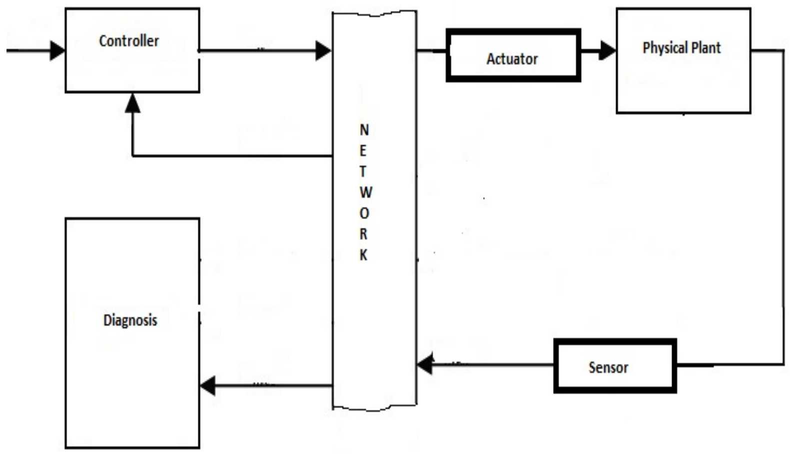

Figure 1: Networked control system

The aim of the present paper is to analyse the behaviour of diagnosis system regarding three different networked control system structures, based on the non deterministic network Switched Ethernet. The main objective is to evaluate the importance of the NCS structure on diagnosis remote applications.
The simulation of networks was carried using the Truetime toolbox, as a means of simulation of distributed real-time control systems. The Truetime library provides specific blocks for the network interface modelling. This library was developed in C++ language. All the developed files were compiled in Matlab using an external C++ compiler. Truetime provides few types of networks which can be used for NCS simulation (Ethernet, CAN, Round Robin, TDMA, FDMA, Switched Ethernet and WLAN or ZigBee Wireless networks) [6], [7], [8].
This article is organized as follows: In section 2, different structures of NCS are presented. Section 3 describes the studied NCS. Section 4 presents the effects of the network parameter packet losses on the different considered structures for the previous networks. Finally, conclusions and perspectives are given.

2. NCS STRUCTURES

According to the different possibilities of network connections in the closed loop control and diagnosis system, several NCS structures can be considered [5], [9]:

- ✓ Structure 1: This structure is shown in figure 2. The network is only used to connect sensors to the diagnosis system and the controller. In this case, the delay induced by the network only affects information flow from the sensors to the controller;

- ✓ Structure 2: This structure is shown in figure 3. The network is only used to connect sensors, diagnosis system and controller to actuator. In this case, the delay induced by the network affects only the information flow from the controller to the actuator;
- ✓ Structure 3: This structure is shown in figure 4. The network is used in the closed loop between process, controller and diagnosis module. This structure is the most used and the influence of the network is higher in this case. Indeed, the delay induced by the network operates throughout the system.

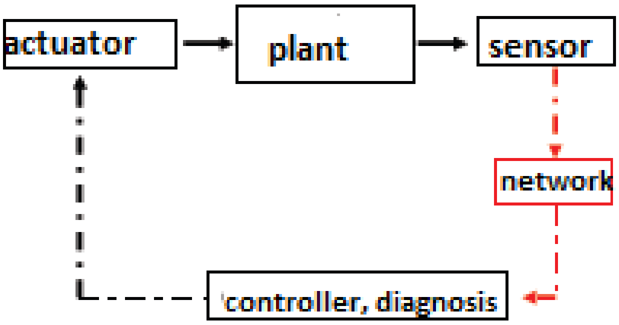

Figure 2: NCS with structure 1

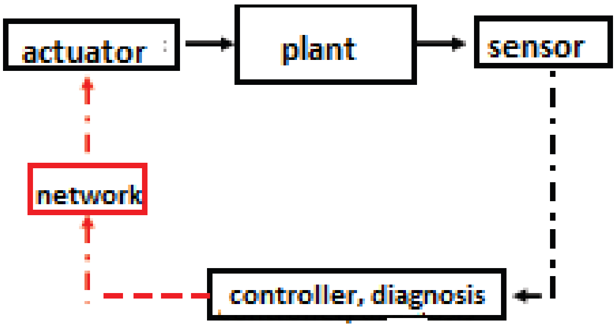

Figure 3: NCS with structure 2

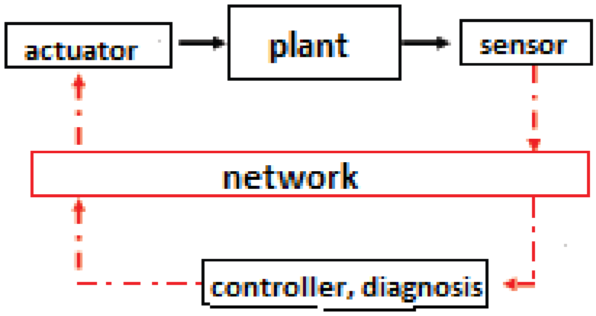

Figure 4: NCS with structure 3

3. DESCRIPTION OF THE STUDIED NCS

Most research in NCS studied the relationships between the network induced delay and the control systems stability. Other works showed the impacts of Quality of Service (QoS) on the stability of feedback control systems. The QoS mechanisms studied were the frame scheduling, the task scheduling, the drop packets, and the protocols. However, only the field buses were considered.
In this section, the goal is to study the network influence on the diagnosis system. Modelling and simulation were performed by Truetime simulator. The studied network is: Switched Ethernet network and a servo problem were chosen in order to follow the command signal and to evaluate diagnosis system performance.

3.1 Switched Ethernet Network

Ethernet was developed in the 1970's and emerged in products in the early 1980s. It is now the dominant local area networking solution at home and in office environment. It is fast and easy to install and the ICs interface are cheap. Despite early attempts to use Ethernet as a real-time communication medium in factories, practitioners were reluctant to adopt this technology because of its intrinsic non determinism.
Originally, Ethernet used a shared medium by using, for example, hub technology. In this case, simultaneous accesses to the medium generate collisions and the transmission is delayed till no collision occurs. It means, in the worse case, when the medium is overloaded; a message can never be transmitted.
Since 1997, new Ethernet versions have been developed and proposed to replace the hub by switches, to connect all the devices in point to point to the switches, to generalise the use of full-duplex mode and to increase the bandwidth. The interest of these technology evolutions is to avoid collisions. But, the collision problem shifted to a congestion problem in switches. The second issue is that the switches generate latencies which have to be taken into account in control systems.
The use of switches to offer real time guarantees on factory communications was suggested and analysed by many authors. The use of switched Ethernet architecture in

real-time systems led to develop the IEEE 802.1 D and IEEE 802.1Q. They offer the possibility of compensation and reduction delay with use the prioritisation packet procedure [1], [10], [11].

3.2 Control System

Consider the PID control of a DC servo described by the following continuous time transfer function:

$$G(s) = \frac{1000}{s(1+s)} \tag{1}$$

The PID-controller was implemented in TrueTime kernel block according to the following equations [8], [12] :

$$\begin{aligned} &P(k) = K.(\beta c(k) - y(k)) \\ &I(k+1) = I(k) + \frac{K_h}{T_i}(c(k) - y(k)) \\ &D(k) = a_d D(k-1) + b_d(y(k-1) - y(k)) \\ &u(k) = P(k) + I(k) + D(k) \end{aligned} \tag{2}$$

Where $a_d = \frac{T_d}{Nh+T_d}$, $b_d = \frac{NkT_d}{Nh+T_d}$,

h, N, T_i, T_d, u, y and c are respectively sampling period, number of sampling, integration constant, derivative constant, control signal, output signal, and reference value.

The controller parameters were chosen to give the system a closed-loop bandwidth of $w_c = 20\ rad/s$ and a relative damping of $\zeta = 0.7$.

The closed loop control system was distributed on a network (Switched Ethernet) and modelled with Truetime simulator. The system model was composed by the network model, the plant model, the actuator node, the sensor node, the controller node and the diagnosis node.

3.3 Diagnosis system

Many methods allow residual generation by using analytical models. These methods are generally classified in three categories: observer-based, parity space and parameter estimation.

All these approaches use a mathematical model to generate residuals. In the simplest case, the residual is obtained as the difference between the system output y and model prediction $\hat{y}$ through the following equation:

$$r_k = y_k - \hat{y}_k \tag{3}$$

$\hat{y}_k$ can be obtained by model simulation from the system measured inputs or by prediction from inputs/outputs. In theory, this residual is equal to zero in the presence of a healthy system and different from zero when a system is defective:

$r_k = 0 \Rightarrow$ No fault, $r_k \neq 0 \Rightarrow$ fault.

Once the residual vector is generated, this one is evaluated i.e. transformed into symptom. Fault appearance is detected once a residual *r* is different from zero. [13], [14], [15].

The Kalman filter used as an observer in the diagnosis system was configured to reconstitute the signal from the measurements. To obtain the residual we simply subtracted this signal to the signal taken from the network over the sensor [16].

Figure 5 presents a description of the diagnosis system used in this study.

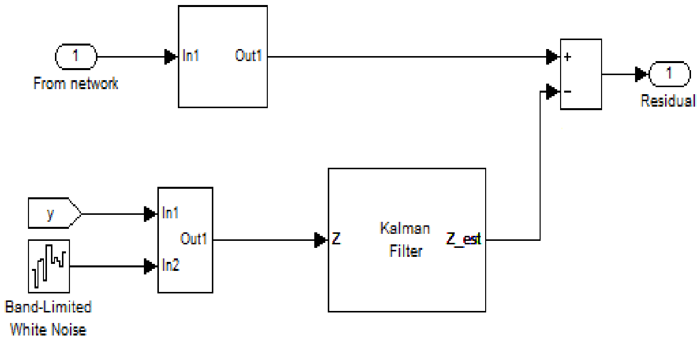

Figure 5: Diagnosis systems description

The threshold was calculated for all structures as minimum and maximum values of the residual.

Generally, faults are classified into two categories: the additive faults which influence a variable y by the addition of the fault f and the multiplicative faults which is obtained by the product of another variable u with f. The faults are modelled as additive terms in the system model, or as parameter changes. The first approach is usually appropriate to sensors and actuators faults, whereas the second is intended for faults on process dynamics level. In this work, we used the approach based on observers for obtaining the residuals and we considered additive simple faults. The diagnosis system objective is to detect possible fault f of the velocity sensor.

3.4 Truetime/Simulink Models of the Different Structures of NCS

Figures 6, 7 and 8 show the adopted models of the considered NCS. Truetime toolbox [8], [17] was used to simulate Switched Ethernet network functionalities and to create models of sensor, actuator, controller and diagnosis system.

In figure 6, that represents NCS structure 1 model, the Truetime toolbox was used to model the network, diagnosis system (node 5), sensor (node 3) and controller (node 4). The actuator is connected directly to controller.
With NCS structure 2 model, figure 7, the Truetime toolbox was used to model the network, controller (node 4) and actuator (node 2). The sensor is connected directly to the controller and the diagnosis system (node 5). The regulation algorithm was done and then the set point (reference signal) was given to actuator over network.
All components communicate over the network In figure 8, that represents NCS structure 3 model. Truetime was used to model the network and all these components like nodes.

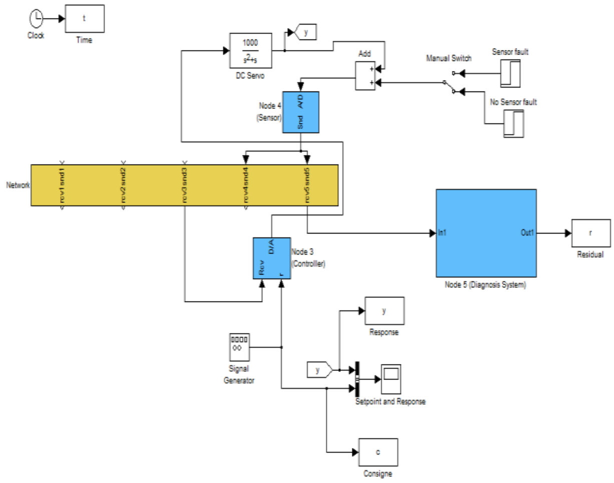

Figure 6: Adopted model of NCS with structure 1

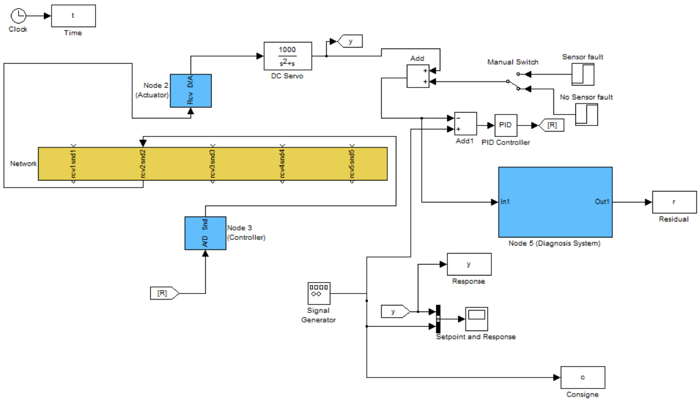

Figure 7: Adopted model of NCS with structure 2

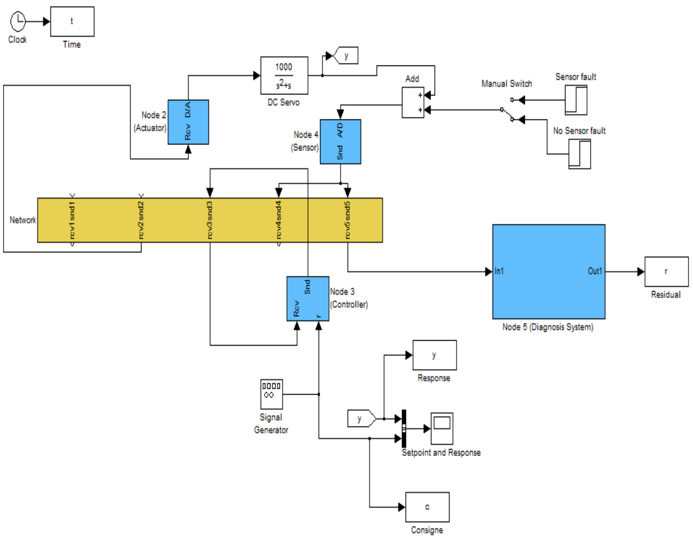

Figure 8: Model of NCS with structure 3

4. NETWORK PARAMETER EFFECTS ON DIAGNOSIS SYSTEMS WITH DIFFERENT STRUCTURES OF NCS

4.1 Introduction

The Switched Ethernet network is studied to show the influence of network on feedback control loop and diagnosis system [1].
The chosen parameters are: the bit rate is 100 M-bits/s and the frame size is 64 Bytes;

Two cases were studied, at first the network was used with ideal assumptions, then the network was used with losses packet (information).
In all cases, we assumed that the congestion does not generate the drop packets. This simulates situation where the buffers in network devices were well dimensioned.

4.2 Network with ideal assumptions

Firstly, the system was simulated in the ideal case. Thus the network introduced no packet losses and the delay depended only on the traffic generated by the real-time system [18]. Therefore the network was not shared with other applications.
Figures 9, 10 and 11 show the behavior of the system on Switched Ethernet network according to the three structures of the NCS.

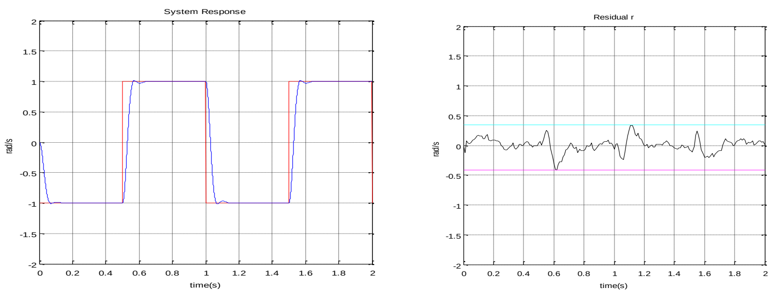

Figure 9: Output y and residual r (Switched Ethernet, adopted NCS with structure 1)

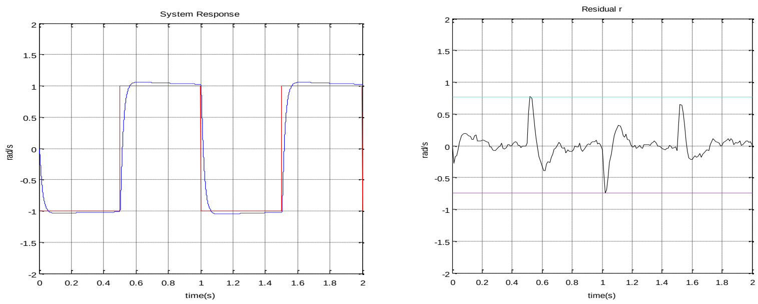

Figure 10: Output y and residual r (Switched Ethernet, adopted NCS with structure 2)

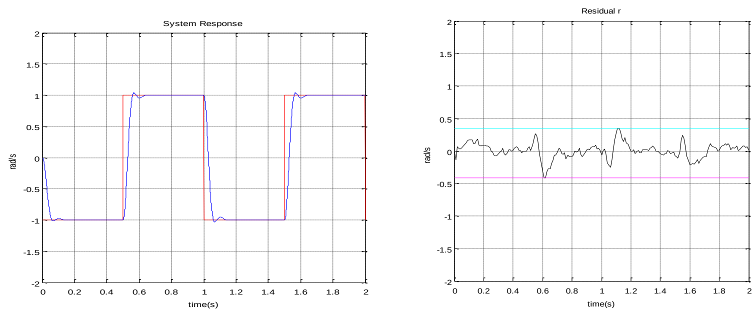

Figure 11: Output y and residual r (Switched Ethernet, adopted NCS with structure 3)

In the three cases, the outputs followed the references, the systems were stable and the diagnosis systems were correctly functioning. Residuals are less than calculated thresholds.

Figures 12, 13 and 14 show the behaviour of the system and the diagnosis system where the fault occurred at 0.8 s (step signal with amplitude 0.1 rad/s) in the cases of the three structures of the NCS.

In the three cases, system responses were affected by fault occurrence.

Residuals showed the occurrence of fault at 0.8 s and exceeded the calculated threshold.

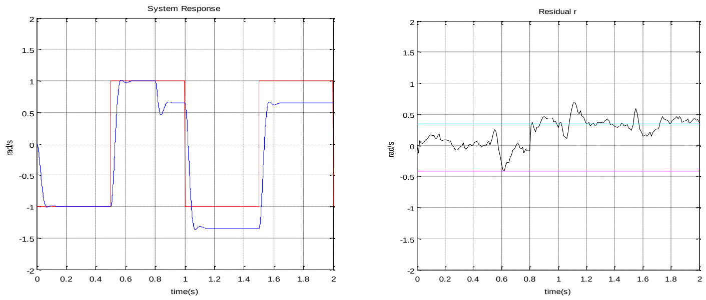

Figure 12: Output y and residual r results (Switched Ethernet, NCS structure 1, sensor fault f)

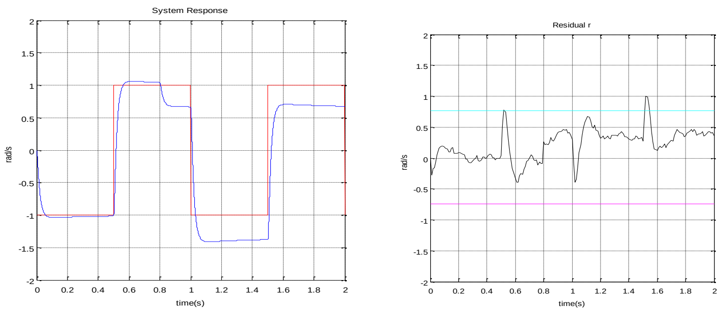

Figure 13: Output y and residual r results (Switched Ethernet, NCS structure 2, sensor fault f)

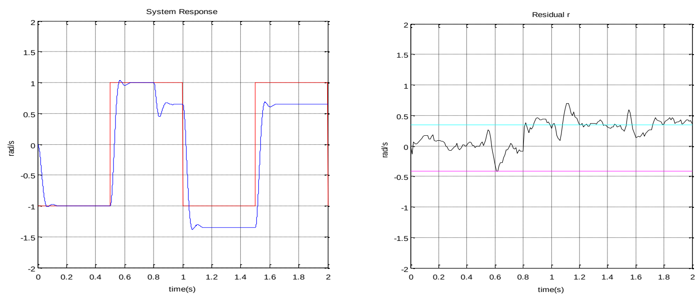

Figure 14: Output y and residual r results (Switched Ethernet, NCS structure 3, sensor fault f)

4.3 Lost information by the Network

In this section, three percentages 10%, 20% and 30% of packet losses are analysed.

Figures 15, 16 and 17 display the system response and the diagnosis system behaviour in the three different structures of NCS when the Switched Ethernet network was assumed to be affected by 10% of packet losses.

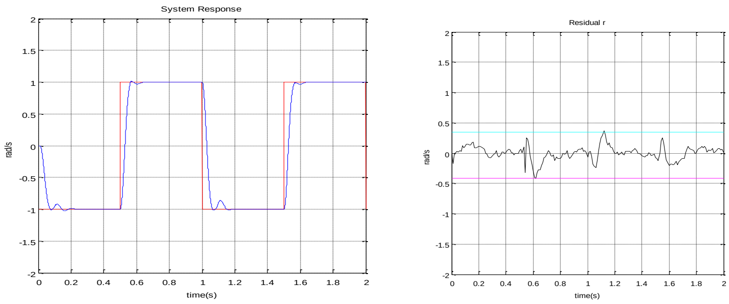

Figure 15: Output y and residual r (Switched Ethernet, 10% of packet losses, structure 1)

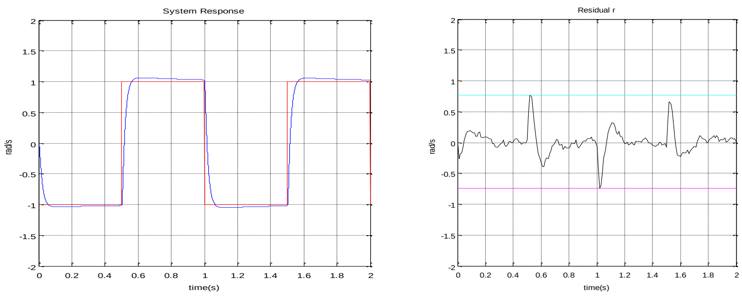

Figure 16: Output y and residual r (Switched Ethernet, 10% of packet losses, structure 2)

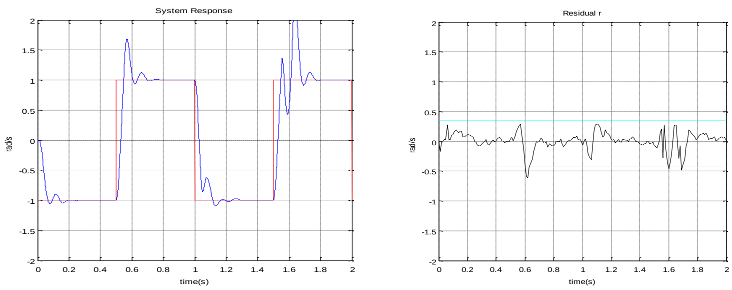

Figure 17: Output y and residual r (Switched Ethernet, 10% of packet losses, structure 3)

At 10% of packet losses and in the presence of sensor fault f, behaviors of response y and residual r changed and are represented in figures 18, 19 and 20.

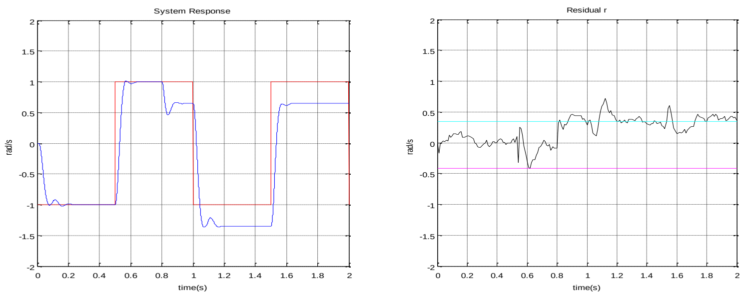

Figure 18: Output y and residual r (Switched Ethernet, 10% of packet loses, with sensor fault f, NCS structure 1)

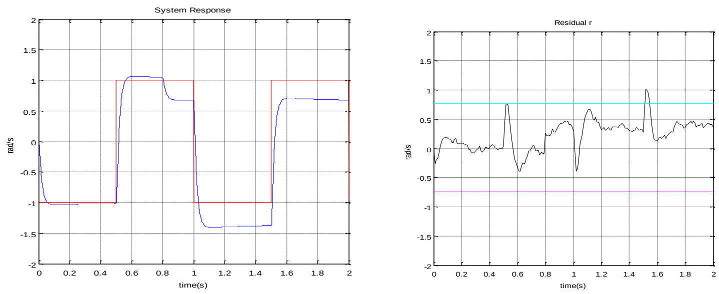

Figure 19: Output y and residual r (Switched Ethernet, 10% of packet loses, with sensor fault f, NCS structure 2)

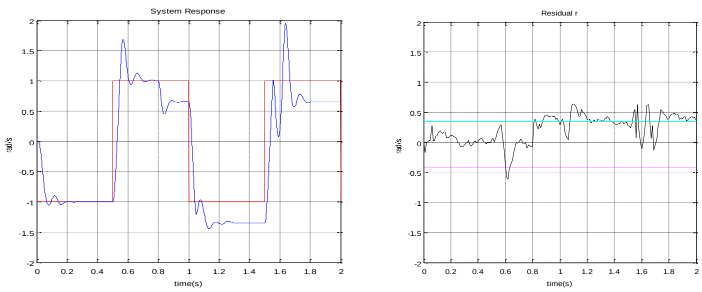

Figure 20: Output y and residual r (Switched Ethernet, 10% of packet loses, with sensor fault f, NCS structure 3)

NCS with structure 3 present an overshot greater than 5%. Other experiences with a percentage of packet losses greater than 10% show that the system becomes unstable and the diagnosis system is incorrectly functioning. Simulations are thus carried out only with the two structures (structure 1 and structure 2).

Figures 21 and 22 shows the behaviours of output y and residual r with 20% of packet losses, when structure 1 of NCS and structure 2 of NCS were adopted respectively. This shows that with structure 1, we had an overshot greater than 5% for the system response and false alarm for the diagnosis system.
With structure 2, the system was stable and the diagnosis system functioned correctly.

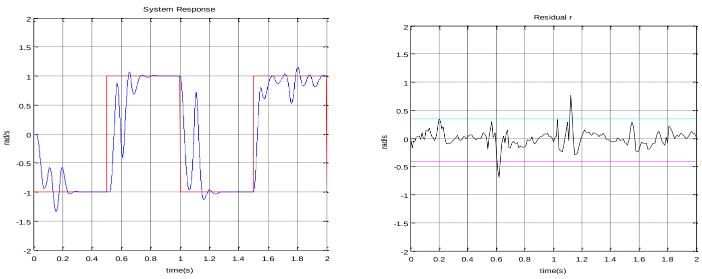

Figure 21: Output y and residual r (Switched Ethernet network, 20% of packet losses, NCS structure 1)

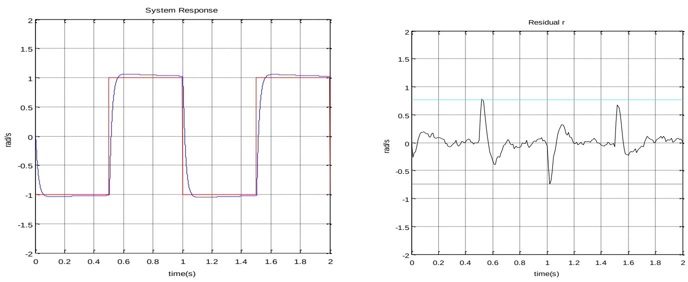

Figure 22: Output y and residual r (Switched Ethernet network, 20% of packet losses, NCS structure 2)

When we consider only structure 2, figures 23 and 24, show the behavior of the residual and the system response at 30% of packet losses with and without sensor fault.
The system was stable and the diagnosis system functioned correctly.

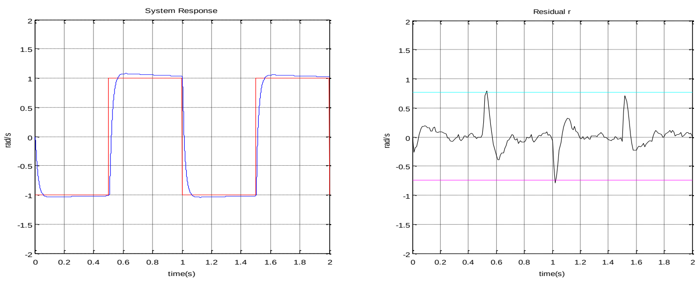

Figure 23: Output y and residual r (Switched Ethernet network, 30% of packet loses, NCS structure 2, no sensor fault f)

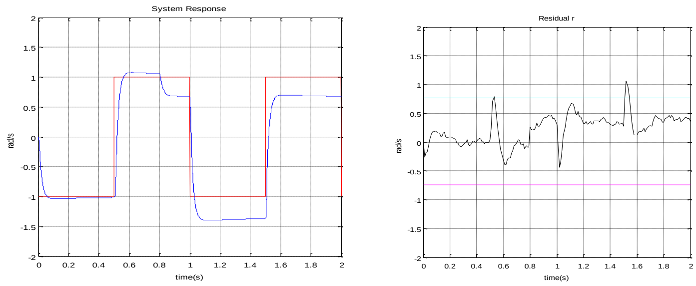

Figure 24: Output y and residual r (Switched Ethernet network, 30% of packet loses, NCS structure 2, in the presence of sensor fault f)

The difference between the three adopted structures is the link of the network, with the controller, the actuator, the diagnosis system, and the sensor. Results show that the system according to structure 3 is very sensitive to of packet losses (loss of performance from 10% of packet losses). Structure 1 gave acceptable performance up to 20% of packet losses. Beyond this level, only structure 2 could keep a good performance for the diagnosis system. This is explained by the arrangement of the sensor relative to the network, the fact that these components were connected to the network, increases the sensitivity of the global system to the packet losses, this is the case of structure 3 where all nodes wereconnected to the network.
In structure 2, the losses only affect the signal to the actuator from the network, which explains its performance.
For structure 1, packet losses affect the sensor, the controller and the diagnosis system signals which makes it less robust to packet losses than the latter.

5. CONCLUSION AND PERSPECTIVES

In this paper, the effect of packet losses on the NCS was investigated for different NCS structures. Three structures were considered to demonstrate NCS sensitivity to

packet losses. This study showed that the structure of NCS has an effect on packet losses sensitivity.
Structure 3, despite its sensitivity to packet losses, is the most standardized and widely used as an NCS structure. The fact that all system components communicate across the network, provides a better flexibility of implementation, use and maintenance.
In future work, remedies effecting of packet losses on the diagnosis system of NCS with structure 3 will be studied and other networks will be used for performance comparison.

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