A New Fault Detection Scheme for Networked Control Systems Subject to Packet Dropout: A Quadrotor Application

Mariem Atoui[†], Kaouther Ibn Taarit[††] and Moufida Ksouri[†]

[†]Analysis Conception and Control of Systems Laboratory, National Engineering School of Tunis, University of Tunis El Manar, Tunis, Tunisia
[††]National Engineering School of Monastir, Analysis Conception and Control of Systems Laboratory, University of Monastir, Monastir, Tunisia

Summary

This paper considers the problem of attitude sensor fault diagnosis in a quadrotor helicopter. We propose a novel residual generation and evaluation strategy for a Networked control system, which is described by linear time variant systems. In order to enhance robustness to network-induced delay, packet dropout in the controller-to-actuator link as well as sensitivity to unknown input and sensor faults, a parity relation based residual generator and evaluator is proposed. The proposed method is assessed on a mini-helicopter quadrotor prototype to validate the theoretical findings. Simulation results demonstrate the accuracy which can be provided for sensor fault detection by parity relations approach in simultaneous presence of delay and packet dropout. Presence of communication network in the control loop introduces several constraints such as network-induced delay and packet dropout which all might be potential sources of poor performance. Our proposed design is relevant, especially because of both of these difficulties are simultaneously considered in the conception of residual generation and evaluation module and because of its simplicity.

Key words:
Networked control systems, Fault detection, Parity space, Packet dropout, Delay, Quadrotor.

1. Introduction

Networked Control Systems (NCSs) have paid an increasing attention in the automatic control community for the last few years. Thanks to their various advantages such as less wiring, easy maintenance and diagnosis and lower installation cost, which make NCSs a brilliant framework for analysis, control and diagnosis, see, [1], [2], [3], [4] and the references therein. And due to these distinctive advantages, these systems have many applications in various areas, such as robotics, automotive, advanced aircrafts, and others. As example, Unmanned Aerial Vehicles (UAVs) are considered networked control systems. Particularly, the quadrotor represents a simple example of UAVs, has relatively cheap and accessible-to-fly, therefore it has been simply used to implement and test methods in fault diagnosis and fault tolerant control. Nevertheless, the introduction of communication networks in the control loops may leads to several new challenges and undesirable effects, such as network-induced delays and packet dropout.

Due to this challenging structure of NCSs, research on Fault Detection (FD), which is required to improve safety and efficiency of dynamic systems, is becoming a very popular area of research, see, for example, [5], [6], [7]. Network-induced delay [8], [9], [10] and packet dropout [11], [12], [13] are the fundamental particularities of the network which have to be considered in the conception of FD approach. In the literature, several studies have considered the simultaneous presence of packet dropout and network induced delay in stability study, control and diagnosis of NCSs framework [14], [15], [16].

Model-based FD [17] approaches have been recently the subject of growing interest. Those techniques can be classified into observer based approaches [18], [11], [19], [20], Kalman filter based approaches [5] and parameter identification based approaches [21], [22] and parity space based approaches [23], [7], [24]. In model-based fault detection, parity space method is considered one of the most widespread approaches for fault detection and thus, because of its various advantages. Indeed, in case of complex systems (NCSs framework with considering many particularities induced by network), kalman filter, observer and parameter estimation based algorithms for fault detection may lead to a good results, detect efficiently faults but its demand high computational time. However, Parity space achieves a reasonable computational time even if many problems induced by network are considered. In addition, the proposed fault detection method is able to achieve a good compromise between the computational time and accuracy of the fault detection.

Certainly, many results have been obtained on NCS fault detection based on Parity Relation (PR) [25], [26] [7]. However research on fault detection based on PR for NCSs subject to packet dropout and network induced delay simultaneously, still presents an important area of research.

To the author's knowledge, a few studies have examined fault detection problems based on Parity Space Approach in a NCSs framework characterized by the simultaneous

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presence of variable network-induced delay and packet losses in the controller-to-actuator link. In ¥cite{wang2009residual}, a parity space-based design for NCSs has been proposed to treat stochastic system parameters caused by random packet dropout. Nevertheless, Network induced delay has not been taken into account in this fault detection scheme. Motivated by these raised observations, our present work joins in the continuity of these researches. Therefore, the main contribution is based on the extension of the parity space approach previously developed in [12] that proposes a residual generator which considers both of network induced delay and packet dropout.

The main idea is to generate a sensor fault detection algorithm based on Parity Space Approach for a quadrotor model with considering the variable network-induced delay and the packet dropout in the controller-to-actuator link simultaneously. A threshold is computed in a residual evaluation stage in a way that faults will be distinguished from disturbances. Hence, residual reveals the faults in presence of disturbance inputs.

The remainder of this paper is structured as follows: First, in section 2, we describe the unmanned aerial vehicle named afterward quadrotor then we present the principle of parity space based fault detection for NCSs. Section 3 proposes a residual generation and evaluation design signal is determined considering the constraints induced by network. The proposed approach illustrated by the quadrotor benchmark in section 4, the last section is devoted to conclusions.

2. Research Method

2.1 Description of the Quadrotor Dynamics

Quadrotor of the GIPSA-Lab or Unmanned Aerial Vehicle(UAV) is a nonlinear system that embeds a Controller Area Network (CAN) and an Inertial Measurement Unit(IMU). The quadrotor under study is controlled by the rotational speeds of four blades which are operated by the four electric motors, as shown **Fig. 1.**

Fig. 1 Quadrotor mini-helicopter.prototype of GIPSA-lab.

In this subsection, the mini-helicopter model is first given. The attitude is modeled with the Euler-angle representation, which provides an intuitive model for the linearized quadrotor version.

Remark 1. Note that this work is not addressed to the design of a control law and we will focus only with the linearized model of the UAV.

In the remainder of this paper, the linear dynamics of the quadrotor under the fault effect described in Appendix 1. is governed by the following state space model [28]:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu_p(t) + E_d d(t) \\ y_p(t) = Cx(t) + E_f f_1(t) + E_f f_2(t) \end{cases} \tag{1}$$

$A, B, C, E_d, E_{f_1}, E_{f_2}$ are matrices of appropriate dimension. Where $x(t) \in \Re^n$ is the state vector, $u_p(t) \in \Re^p$ denote the input vector, $d(t) \in \Re^l$ is the unknown input vector (perturbation), $y(t) \in \Re^m$ denote the output vector, $f_1(t) \in \Re^q$ and $f_2(t) \in \Re^q$ are two additives faults which may act the sensors of the plant. The following hypothesis are taken into account for the remainder of the paper.

Assumption 1. We suppose that the residual generation and evaluation algorithms are executed instantaneously at every sampling period k. Based on this hypothesis, if the control input is stored constant over each sampling interval h, and if we assume that fault inputs show slow dynamics, the dynamic of the system under network induced effects and fault effects, after discretization is described by:

$$\begin{cases} x(k+1) = \Phi x(k) + \Gamma u_p(k) + \Psi d(k) \\ y_p(k) = Cx(k) + E_f f_{y1}(k) + E_f f_{y2}(k) \end{cases} \tag{2}$$

where

$$\Phi = e^{Ah}, \Gamma = \int_0^h e^{As} B ds \ and \ \Psi = \int_0^h e^{As} E ds. \tag{3}$$

2.2 Description of the method

Indeed, there are many approaches to the conception for the fault detection module. Thus, developing a new approach does not the main purpose of this paper. In the rest of the paper, it is supposed that the FD system based on parity space is connected to the plant via a communication network. Therefore, we take into account the network-induced delay and the packet dropout (in both sensor-to-controller link and controller-to-actuator link) as shown in Fig. 2 .

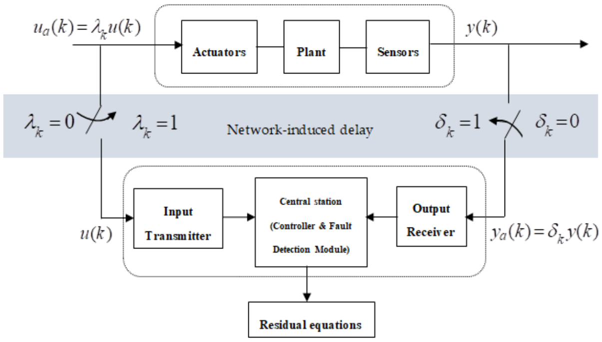

Fig. 2 Block diagram of diagnosis procedure of a network controlled system under delay and packet dropout constraints.

In a first step, we consider the case where the network induced delay τ_k is zero and there is no packet dropout in the networks. The idea is to design a residual generator based on parity space. As proved in [29], a parity relation based residual generator for system (2) can be described by:

$$r_s(k)=V_s[y_s(k)-H_{u,s}u_s(k)] \tag{4}$$

where s is the order of parity space and V_s represents the parity vector satisfying $V_sH_{O,s}=0$, and

$$V_s=\left[v_{s,0},v_{s,1},\cdots,v_{s,s}\right]\in R^{m(s+1)}, \tag{5}$$

where $H_{o,s}$ represents the extended observability matrix.

$$H_{o,s}=\left(C \quad CA \quad CA^2 \quad \cdots \quad CA^s\right)^T, \tag{6}$$

y_s denote the vector of the sensor measurement received by the controller regrouped over a horizon s. Similarly, u_s represents the vector of the controller input regrouped over the same horizon.

$$\begin{aligned} y_s(k)&=[y(k-s) \quad y(k-s+1) \quad \cdots \quad y(k)]^T,\\ u_s(k)&=[u(k-s) \quad u(k-s+1) \quad \cdots \quad u(k)]^T. \end{aligned} \tag{7}$$

Here $H_{u,s}$ denotes the Toeplitz matrix and is defined as

$$H_{u,s}=\begin{pmatrix} B & 0 & \cdots & 0\\ CB & B & \ddots & \vdots\\ \vdots & \ddots & \ddots & 0\\ CA^{s-2}B & \cdots & CB & B \end{pmatrix} \tag{8}$$

Since the residual signal r_s is computed to detect faults. According to [9] and using (2) and (4), the dynamics of (4) can be written as follows

$$\begin{aligned} r_s(k)=V_s[&H_{d,s}d_s(k)+H_{f,s}f_{y1,s}(k)\\ &+H_{f,s}f_{y2,s}(k)], \end{aligned} \tag{9}$$

where $H_{d,s}$, $H_{f,s}$ are called Toeplitz matrix and are defined as

$$\begin{aligned} H_{d,s}&=\begin{pmatrix} E_d & 0 & \cdots & 0\\ CE_d & E_d & \ddots & \vdots\\ \vdots & \ddots & \ddots & 0\\ CA^{s-2}E_d & \cdots & CE_d & E_d \end{pmatrix},\\ H_{f,s}&=\begin{pmatrix} E_f & 0 & \cdots & 0\\ CE_f & E_f & \ddots & \vdots\\ \vdots & \ddots & \ddots & 0\\ CA^{s-2}E_f & \cdots & CE_f & E_f \end{pmatrix}. \end{aligned} \tag{10}$$

and d_s can be defined as the vector of the unknown inputs regrouped over a horizon s. Similarly, $f_{y1,s}$ and $f_{y1,s}$ denote the vectors of the sensors faults regrouped over the same horizon s.

$$\begin{aligned} d_s(k)&=[d(k-s) \quad d(k-s+1) \quad \cdots \quad d(k)]^T,\\ f_{1,s}(k)&=\left[f_1(k-s) \quad f_1(k-s+1) \quad \cdots \quad f_1(k)\right]^T,\\ f_{2,s}(k)&=\left[f_2(k-s) \quad f_2(k-s+1) \quad \cdots \quad f_2(k)\right]^T. \end{aligned} \tag{11}$$

3. Parity Space-Based Fault Detection for NCSs

3.1 Parity Relation Residual Generation

In a second attempt, we consider the case where the network induced delay τ_k is non-zero and there is packet dropout in the network.

Assumption 2. Let us assume that τ_k denotes the unknown time-varying induced delay at the k sampling step and $\tau_k=\tau_k^{sc}+\tau_k^{ca}$ is smaller than one sampling period $\tau_k\le T_e$, τ_k^{ca} and τ_k^{sc} are the controller-to-actuator link and the sensor-to-controller link.

Remark 2. For data acquisition it is supposed that the actuator is event driven, i.e. calculation of the actuator signal (new control input) is trigged as soon as the new control or actuator information is received and the sensor is time-driven with a constant sampling period, as it showed on Fig. 3.

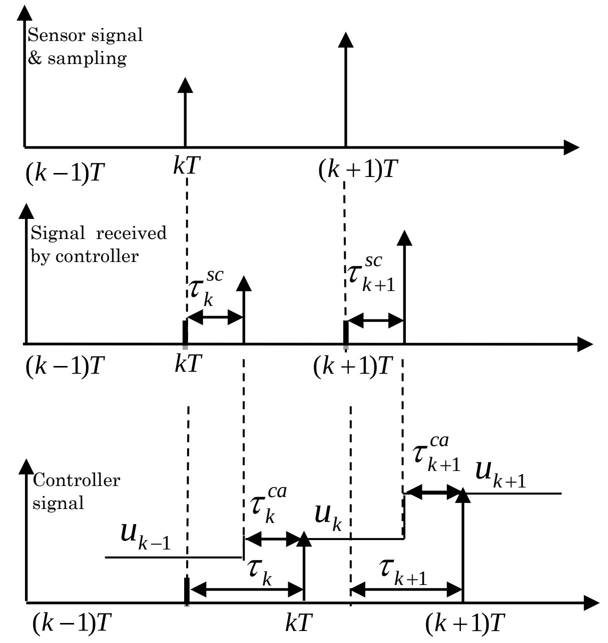

Fig. 3 Delay timing for a networked control system.

In the case where the network-induced delay is non-zero, the NCS model becomes

$$\begin{cases} x(k+1) = \Phi x(k) + \Gamma u_p(k) + q_{\tau_k} + \Psi d(k) \\ y_p(k) = Cx(k) + E_f f_{y1}(k) + E_f f_{y2}(k) \end{cases} \tag{12}$$

With the definitions:

$$q_{\tau_k} = \Gamma_{\tau_k}(u(k) - u(k-1)), \Gamma_{\tau_k} = \int_{h-\tau_k}^{h} e^{At} B dt \tag{13}$$

Here, $q_{\tau_k} \in \Re^{nxp}$ represents an unknown variable vector signal introduced by the delay τ_k.

Thus, the dynamics of residual generator of (9) can be reformulated as

Where

$$\begin{aligned} r_s(k) = V_s[&H_{d,s} d_s(k) + H_{q,s} q_s(k) \\ &+ H_{f,s} f_{y1,s}(k) + H_{f,s} f_{y2,s}(k)], \end{aligned} \tag{14}$$

$$q_s(k) = \begin{pmatrix} q_{\tau_k}(k-s) & q_{\tau_k}(k-s+1) & \cdots & q_{\tau_k}(k) \end{pmatrix}^T \tag{15}$$

and

$$H_{q,s} = \begin{pmatrix} I_{nxn} & 0 & \cdots & 0 \\ CI_{nxn} & I_{nxn} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ CA^{s-2} I_{nxn} & \cdots & CI_{nxn} & I_{nxn} \end{pmatrix}, \tag{16}$$

and I_{nxn} denotes an identity matrix.

Assumption 3. In practice, control signals and outputs measurements sent through networks links may be modified over transmission. Then, we consider the unreliability of the controller-to-actuator link. In the following, we will use $u_p(k)$ the controller input, $u(k)$ to represent the control signal produced by the controller. Since the controller and the actuator are remotely related, the actuator input u_p and the sensor measurement y_p are transmitted from the central station by the controller-to-actuator link and by the sensor-to-controller link similarly.

Remark 3. We assume that the signal $u(i)$ $(k-s \le i \le k)$ in $u_s(k)$ can be loss or corrupted over transmission i.e $u(i)$ may not be the exact input of the plant. There is two strategies which can be adopted:

- $u_p(k) = 0$: the current control input is equal to zero.
- $u_p(k) = u_p(k-1)$: the current control input is equal to the last available control signal.

As will be demonstrated later, both of these two stratigies can be adopted as far as fault detection module design is concerned.

Remark 4. In this work, we consider the case when packet dropout occurs only in the controller-to-actuator link, the packet dropout in the sensor-to-actuator link are neglected. Let us indicate that packet dropout in the controller-to-actuator link can be descibed by:

$$u_{\Delta,s}(k) = u_{p,s}(k) - u_s(k). \tag{17}$$

$u_{p,s}(k)$ represents the vector of the controller inputs regrouped over the window s, and

$$u_{p,s}(k) = \begin{pmatrix} u_p(k-s) & u_p(k-s+1) & \cdots & u_p(k) \end{pmatrix}^T \tag{18}$$

In this paper, the main contribution is to design a residual generator based on parity which ensure the robustness to a variable network induced delay and to a packet dropout in the actuator-to-actuator link.

Then, according to (4) the residual signal for system (11) can be described by:

$$\begin{aligned} r_s(k) = V_s \Big(& y_{p,s}(k) - y_{p,s}(k) + y_s(k) \\ & - H_{u,s}(u_{p,s}(k) - u_{p,s}(k) + u_s(k)) \Big). \end{aligned} \tag{19}$$

We use (13), the dynamics of (18) becomes

$$\begin{aligned} r_s(k) = V_s \Big(& (y_{p,s}(k) - H_{u,s} u_{p,s}(k)) \\ & - (y_{p,s}(k) - y_s(k)) + H_{u,s}(u_{p,s}(k) - u_s(k)) \Big), \end{aligned} \tag{20}$$

or even

$$\begin{aligned} r_s(k) = V_s \Big(& H_{d,s} d_s(k) + H_{f,s} f_{y1,s}(k) + H_{f,s} f_{y2,s}(k) \\ & - (y_{p,s}(k) - y_s(k)) + H_{u,s}(u_{p,s}(k) - u_s(k)) \Big), \end{aligned} \tag{21}$$

Where

$$y_{p,s}(k) = \begin{pmatrix} y_p(k-s) & y_p(k-s+1) & \cdots & y_p(k) \end{pmatrix}^T . \tag{22}$$

Remark 5. In this work, we consider the case when packet dropout occurs only in the controller-to-actuator link, the packet dropout in the sensor-to-actuator link are neglected. Therefore, (20) can be rewriting into

$$\begin{aligned} r_s(k) = V_s [& H_{d,s} d_s(k) + H_{f,s} f_{y1,s}(k) \\ & H_{f,s} f_{y2,s}(k) + H_{q,s} q_s(k) + H_{u,s} u_{\Delta,s}(k)] \end{aligned} \tag{23}$$

Clearly, it appears that the residual signal $r(k)$ depends on the two sensors faults, the unknown input, packet dropout and network-induced delay.

3.2 Parity Relation Residual Evaluation

In this section, problems of residual evaluation are avoided by parity space approach, for under the condition that characteristics of packet dropout in the controller-to-actuator link are governed by a Bernoulli process [23].

However, there is always a trade-off in the selection of threshold. Indeed, a small threshold can lied to false alarms caused by unknown disturbance or the undesirable effects induced by network, a large threshold may lied to non-detection problems.

For decision purpose, a certain threshold $J_{th,k}$ should be provided:

$$\begin{cases} \|r(k)\|_2 < J_{th,k} \Rightarrow \text{no fault is detected} \\ \|r(k)\|_2 \geq J_{th,k} \Rightarrow \quad \text{a fault is detected} \end{cases} \tag{24}$$

We consider (22) in the absence of fault, i.e. $f_{y1}(k)$ and $f_{y2}(k)$ are zeros, then

$$r(k) = V_s [H_{d,s} d_s(k) + H_{q,s} q_s(k) + H_{u,s} u_{\Delta,s}(k)]. \tag{25}$$

Therefore, we have

$$\begin{aligned} \|r(k)\|_2 &= \left\| V_{s,k}^{opt} (H_{d,s} d_s(k) + H_{u,s} u_{\Delta,s}(k) + H_{q,s} q_s(k)) \right\|_2 \\ &\leq \bar{\sigma}(V_{s,k}^{opt} H_{d,s}) \|d_s(k)\|_2 + \bar{\sigma}(V_{s,k}^{opt} H_{u,s}) \|u_{\Delta,s}(k)\|_2 \\ &\quad + \bar{\sigma}(V_{s,k}^{opt} H_{q,s}) \|q_s(k)\|_2 \end{aligned} \tag{26}$$

where $\bar{\sigma}(\bullet)$ represents the maximum singular value of matrix $(\bullet)$. Besides, in the following, we assume that:

$$\begin{aligned} & \|d(k)\|_2 \leq \sup_k \sqrt{d(k)^T d(k)} \square \delta_d , \\ & \|q(k)\|_2 \leq \sup_k \sqrt{q(k)^T q(k)} \square \delta_d \\ & \textit{and } \|u_\Delta(k)\|_2 \leq \sup_k \sqrt{u_\Delta(k)^T u_\Delta(k)} \square \delta_u . \end{aligned} \tag{27}$$

According to (25) and using (26), the threshold can be set as:

$$\begin{aligned} J_{th,k} &= \bar{\sigma}(V_{s,k}^{opt} H_{d,s}) \sqrt{s+1} \delta_d + \bar{\sigma}(V_{s,k}^{opt} H_{q,s}) \sqrt{s+1} \delta_q \\ &\quad + \bar{\sigma}(V_{s,k}^{opt} H_{u,s}) \|u_{\Delta,s}(k)\|_2 \end{aligned} \tag{28}$$

Otherwise, the threshold is governed by:

$$\begin{aligned} J_{th,k} &= \bar{\sigma}(V_{s,k}^{opt} H_{d,s}) \sqrt{s+1} \delta_d + \bar{\sigma}(V_{s,k}^{opt} H_{q,s}) \sqrt{s+1} \delta_q \\ &\quad + \bar{\sigma}(V_{s,k}^{opt} H_{u,s}) \sqrt{i} \delta_u . \end{aligned} \tag{29}$$

4. Results and Discussions

In order to illustrate the effectiveness of our design we apply the proposed results to a real quadrotor prototype of GIPSA-labo [23]. It's supposed that the reference input is a square signal with variable amplitude and the sampling period is $h = 0.01$ s. The network-induced delay is a variable signal. In addition, we suppose that the unknown input (perturbation) is normally and independent distributed random signal. Suppose a first sensor fault $f_1(k) = 10$ occurs at $k = 1000$ and a second sensor fault $f_2(k) = 5$ occurs at $k = 1500$.

Note that we limit ourselves to one attitude sensor and then, the linearized discrete model of the prototype described by (1) is governed by:

$$A_0 = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ \frac{1}{I_{f_x}} \end{bmatrix}, C = \begin{bmatrix} 0 & 1 \end{bmatrix},$$

$$E_d = \begin{bmatrix} 0.01 & 0.01 \\ 0.01 & 0.01 \end{bmatrix}, E_f = \begin{bmatrix} 1 \\ 0 \end{bmatrix}. \tag{30}$$

Then, the residual signal is calculated within (13) as show **Fig. 4** and after within (22) as illustrate **Fig. 5.**

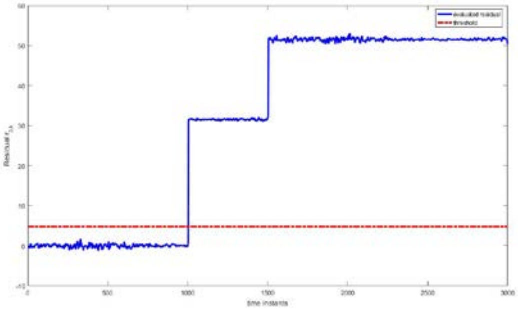

Fig. 4 Residual signal generated by parity space approach without take in account packet dropout.

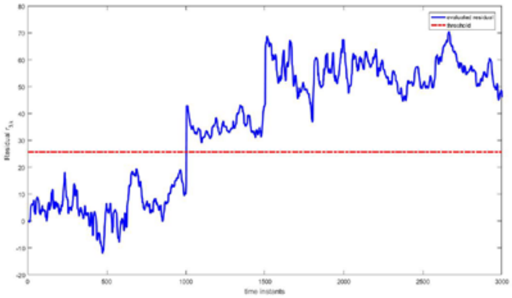

Fig. 5 Residual signal taken into account the influence of packet dropout and network induced delay.

A parity space-based residual generator is designed with order 3 for detect faults that may occur in the first attitude sensor of quadrotor system which is affected by two additives steps sensor faults. The residual signals shown in **Figure 5.** have a good robustness to the network induced delay, packet dropout in controller-to-actuator link and unknown input also a good sensitivity to faults.

From the result in **Figure 4.** we can note that the threshold is too small which may yields to nondetection when we have a small faults. However, results in **Figure 5.** we can see that the evaluated threshold is less than the residual even thought in the presence of packet dropout in the controller-to-actuator link and proves effectiveness of our proposed method.

5. Conclusion

In this paper, we propose an approach that aim at fault detection for NCSs subject to network-induced delay and packet losses in the controller-to-actuator link simultaneously. The main contributions include: (i) residual generation (ii) residual evaluation within the framework of networked control systems. A sensor fault detection module based on parity relation with variable network-induced delay and packet dropout in controller-to-actuator link is developed in this paper. Our approach is illustrated on the quadrotor benchmark developed at The GIPSA-Labo. Furthermore, a comparison with parity space approach without taking into consideration the packet loss shows effectiveness of our results. The results obtained with our design verify that even with applications with deep real-time constraints (presence of network-induced delay, unknown inputs, and packet dropout and sensors fault) the residual generator can detect the presence of fault efficiently. One of our future research works would be the comparison our approach with the others existing model based approaches for fault detection. Moreover, fault tolerant control can be studied in NCSs framework subject to real time constraints.

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Appendix

The quadrotor under study is constituted from four fixed-pitch rotors attached at the four ends of a simple cross frame. The attitude is modeling with the Euler-angle representation, which provides an intuitive linearised model.

Two frames are considered to illustrate the dynamic equations (see **Fig. 6**) :

- *The inertial frame* $N(e_{x_n}, e_{y_n}, e_{z_n})$
- *The body frame* $B(e_{x_b}, e_{y_b}, e_{z_b})$ *connected to the mini-helicopter with its origin (at the centre of mass of the quadrotor).*

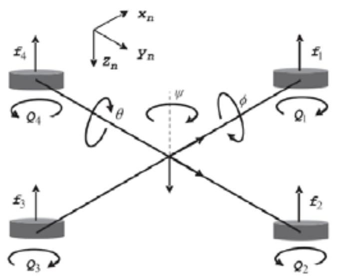

Fig. 6 Quadrotor configuration.

Three rotation angles characterize the quadrotor orientation: with respect to the frame N: yaw (ψ), pitch (θ), and roll (ϕ).

References

[1] J. Chen and R. J. Patton, Robust model-based fault diagnosis for dynamic systems. Springer Science & Business Media, 2012, vol. 3.

[2] [2]C. Aubrun, D. Sauter, and J. Yam´e, "Fault diagnosis of networked control systems," International Journal of Applied Mathematics and Computer Science, vol. 18, no. 4, pp. 525–538, 2008.

[3] W. Zhang, M. S. Branicky, and S. M. Phillips, "Stability of networked control systems," IEEE Control Systems, vol. 21, no. 1, pp. 84–99, 2001.

[4] H. Fang, H. Ye, and M. Zhong, "Fault diagnosis of networked control systems," Annual Reviews in Control, vol. 31, no. 1, pp. 55–68, 2007.

[5] K. Chabir, D. Sauter, M. K. B. Gayed, and M. N. Abdelkrim, "Design of an adaptive kalman filter for fault detection of networked control systems," in Control and Automation, 2008 16th Mediterranean Conference on. IEEE, 2008, pp. 1124–1129.

[6] J. Zhang, M. Lyu, X. Li, and J. Zheng, "Fault detection for networked control system with multiple communication delays and multiple missing measurements," in Networking, Sensing and Control (ICNSC), 2015 IEEE 12th International Conference on. IEEE, 2015, pp. 580–585.

[7] W. Han, Z. Wang, and Y. Shen, "Fault estimation for a quadrotor unmanned aerial vehicle by integrating the parity space approach with recursive least squares," Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, vol. 232, no. 4, pp. 783–796, 2018.

[8] D. Sauter and C. Aubrun, "Fault diagnosis of networked control systems: Robustness enhancement," in Control and Automation, 2009. MED'09. 17th Mediterranean Conference on. IEEE, 2009, pp. 634–639.

[9] H. Ye and S. X. Ding, "Fault detection of networked control systems with network-induced delay," in Control, Automation, Robotics and Vision Conference, 2004. ICARCV 2004 8th, vol. 1. IEEE, 2004, pp. 294–297.

[10] H. Ye and Y. Wang, "Application of parity relation and stationary wavelet transform to fault detection of networked control systems," in Industrial Electronics and Applications, 2006 1ST IEEE Conference on. IEEE, 2006, pp. 1–6.

[11] P. Zhang, S. Ding, P. Frank, and M. Sader, "Fault detection of networked control systems with missing measurements," in Control Conference, 2004. 5th Asian, vol. 2. IEEE, 2004, pp. 1258–1263.

[12] Y. Wang, H. Ye, S. X. Ding, G. Wang, and D. Zhou, "Residual generation and evaluation of networked control systems subject to random packet dropout," Automatica, vol. 45, no. 10, pp. 2427–2434, 2009.

[13] Y.Wang, S. X. Ding, P. Zhang,W. Li, H. Ye, and G.Wang, "Fault detection of networked control systems with packet dropout," IFAC Proceedings Volumes, vol. 41, no. 2, pp. 8884–8889, 2008.

[14] J. Xiong and J. Lam, "Stabilization of linear systems over networks with bounded packet loss," Automatica, vol. 43, no. 1, pp. 80–87, 2007.

[15] H. Lin and P. J. Antsaklis, "Stability and persistent disturbance attenuation properties for a class of networked control systems: switched system approach," International Journal of Control, vol. 78, no. 18, pp. 1447–1458, 2005.

[16] W.-A. Zhang and L. Yu, "Modelling and control of networked control systems with both network-induced delay and packet-dropout," Automatica, vol. 44, no. 12, pp. 3206–3210, 2008.

[17] P. M. Frank, "Fault diagnosis in dynamic systems using analytical and knowledge-based redundancy: A survey and some new results," automatica, vol. 26, no. 3, pp. 459–474, 1990.

[18] [A. Zhirabok, A. Y. Suvorov, and A. Shumskii, "Robust diagnosis of discrete systems with delay: Logicdynamical approach," Journal of Computer and Systems Sciences International, vol. 53, no. 1, pp. 47–62, 2014.

[19] N. Sun, Y. Zhang, G. Song, and T. Li, "Design of observer-based quantized control for nonlinear time delay systems," Transactions of the Institute of Measurement and Control, p. 0142331217745581, 2018.

[20] H. Trinh, D. C. Huong, and S. Nahavandi, "Observer design for positive fractional-order interconnected time-delay systems," Transactions of the Institute of Measurement and Control, p. 0142331218757864, 2018.

[21] R. Isermann, "Supervision, fault-detection and fault-diagnosis methodsan introduction," Control engineering practice, vol. 5, no. 5, pp. 639–652, 1997.

[22] M. K. Smail, L. Pichon, M. Olivas, F. Auzanneau, and M. Lambert, "Recent progress in wiring networks diagnosis for automotive applications," COMPEL-The international journal for computation and mathematics in electrical and electronic engineering, vol. 30, no. 4, pp. 1148–1161, 2011.

[23] Y. Song, M. Zhong, J. Chen, and Y. Liu, "An alternative parity space-based fault diagnosability analysis approach for linear discrete time systems," IEEE Access, vol. 6, pp. 16 110–16 118, 2018.

[24] A. Zhirabok and A. Shumsky, "Redundancy relations for the diagnosis of hybrid systems," Journal of Computer and Systems Sciences International, vol. 57, no. 4, pp. 594–607, 2018.

[25] P. S. Kim and E. H. Lee, "A new parity space approach to fault detection for general systems," in International Conference on High Performance Computing and Communications. Springer, 2005, pp. 535–540.

[26] H. Ye, G. Wang, and S. X. Ding, "A new parity space approach for fault detection based on stationary wavelet

transform,” IEEE Transactions on Automatic Control, vol. 49, no. 2, pp. 281–287, 2004.

[27] E. Chow and A. Willsky, “Analytical redundancy and the design of robust failure detection systems,” IEEE Transactions on automatic control, vol. 29, no. 7, pp. 603–614, 1984.

[28] K. Chabir, M. A. Sid, and D. Sauter, “Fault diagnosis in a networked control system under communication constraints: A quadrotor application,” International Journal of Applied Mathematics and Computer Science, vol. 24, no. 4, pp. 809–820, 2014.

[29] S. X. Ding, Model-based fault diagnosis techniques: design schemes, algorithms, and tools. Springer Science & Business Media, 2008.

Mariem Atoui received her engineering degree in electrical and automatic control from the National Engineering School of Gabes (ENIG) in 2014. And she is currently pursuing her PhD degree in the National Engineering School of Tunis. Her research interests include fault detection and diagnosis of networked control systems.

Kaouther Ibn Taarit is currently an Assistant Professor at the National Engineering School of Monastir
(ENIM). She received her engineering degree in Electrical Engineering in 2006, her MS degree in Control and Signal Processing in 2007. In 2010, she obtained her PhD degree from the National Engineering School of Tunis (ENIT) and Central School of Lille (EC-Lille). Her research interests include time delays systems, hybrid systems, parametric identification problems, model predictive control, diagnosis of dynamic systems and Internet of Things (IoT).

Moufida Ksouri is a professor at the National Engineering School of Tunis. She obtained her Engineering Master in 1982 from the École Normale Supérieure de l’Enseignement Technique and her PhD degree in 1999 from the University of Sciences and Technologies, Lille, France. Her research interests cover the system control theory, fault detection and isolation, fault tolerant control, hybrid dynamical systems, time delays systems and Internet of Things (IoT).